AN ASSESSMENT OF CANOPY AND LITTER INTERCEPTION IN COMMERCIAL AND INDIGENOUS FORESTS IN THE KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

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ABSTRACT

Understanding of the hydrological cycle and processes such as interception span as far back as the times of the Renaissance, when Leonardo da Vinci (1452-1519) first described it. However, there remains a gap in the knowledge of both canopy and litter interception in South African forest hydrology. Interception is typically considered to constitute only a small portion of total evaporation and in some models is disregarded or merely lumped with total evaporation, and not considered as a separate process. Interception is a threshold process, as a certain amount of water is required before successive processes such as infiltration and runoff can take place. Therefore an error introduced in modelling interception, especially disregarding it, will automatically introduce errors in the calibration of subsequent models/processes. In this study, field experiments to assess these two poorly understood hydrological processes, *viz.* canopy and litter interception were established for the three main commercial forestry genera in South Africa, namely, *Pinus, Acacia* and *Eucalyptus* as well as an indigenous *Podocarpus henkelii* stand, thus, accounting for interception of "broad leaf", "compound leaf" and "needle leaf" trees in order to provide further insight into these processes. The study took place at two locations in the KwaZulu-Natal Midlands over a period of three years. The first site is the Two Streams catchment, located in the Seven Oaks area, about 70km north-east of Pietermaritzburg where the study on the commercial plantation species took place. The second site was the *Podocarpus henkelii* stand in Karkloof near Howick, 40km north of Pietermaritzburg.

From the field data collected (*cf.* Chapter 2) it was observed that canopy storage capacity, an important parameter governing interception, was not constant and changed with rainfall intensity, with lower intensity events resulting in a higher storage capacity. Building on these findings, a physically based canopy interception model that is based on the well known Gash model was developed, and is referred to herein as the "variable storage Gash model". While canopy interception is dependent on many factors including the storage capacity, potential evaporation, rainfall intensity and rainfall duration, the litter interception is largely dependent on the storage capacity due to the evaporative drivers under the canopy such as radiation, temperature and wind speed being moderated by the above canopy. From these finding, a litter interception model based on idealised drying curves from litter samples collected at the study sites was also developed (*cf.* Chapter 3). From the field data, it was found that the canopy interception for *Eucalyptus grandis, Acacia mearnsii* and *Pinus patula* was 14.9, 27.7 and 21.4% of mean annual precipitation (MAP) respectively. The simulated canopy interception using the "variable storage Gash model" was 16.9%, 26.6% and 23.3% for *E. grandis, A. mearnsii* and *P. patula* respectively. The litter interception measured for *E. grandis, A. mearnsii* and *P. patula* was found to be 8.5, 6.6 and 12.1% of MAP respectively, while the simulated litter interception using the idealised drying curve model corresponded well with the measured results and were 10.1%, 5.4% and 13.4% for

E. grandis, A. mearnsii and *P. patula* respectively. The idealised drying curve model is site and species specific and is therefore not transferable to other locations. Conversely, the "variable storage Gash model" is transferable as it is not site and species specific, and relies on readily measureable and available information. Building on field studies, this was then used to simulate the canopy interception for *Eucalyptus, Acacia mearnsii* and *Pinus* in South Africa (including Lesotho and Swaziland) for all quinary catchments in which commercial forestry could be grown, i.e. a mean annual precipitation of greater than 600 mm.year^{-1} (*cf.* Chapter 4). It was found that, depending on the location and genus, canopy interception loss can be as high as 100 to 300 mm per year or approximately 10% to 40% of MAP. This relates to a mean interception loss of between 1.0 and 3.0 mm per rainday, highlighting the spatial variability of canopy interception. To further investigate the spatial variability of canopy interception, at various spatial scales, remote sensing technology was applied to estimate leaf area index (LAI) for use in modelling/estimating canopy storage capacity and canopy interception (*cf.* Chapter 6). The NDVI, SAVI and Vogelmann 1 vegetation indices were used in the estimation of the LAI. It was found the Vogelmann 1 index produced the best results. As models to estimate canopy interception typically require LAI and storage capacity, it was calculated that the ability to estimate these parameters over large areas is valuable for water resources managers and planners.

An often neglected consideration of canopy and litter interception is its role in determining the water use efficiency (WUE) of a forest stand (*cf.* Chapter 5). This component of the study was undertaken in an indigenous *Podocarpus henkelii* stand as well as a commercial *Pinus patula* stand in Karkloof in the KwaZulu-Natal Midlands. The sap flow (transpiration) was measured in both the *P. henkelii* and *P. patula* stands using the using the Heat Pulse Velocity (HPV) technique in order to determine the productive green water use. The canopy and litter interception was measured in the *P. henkelii* site, but was modelled in the *P. patula* site using the "variable storage Gash" and idealised drying curve models, in order to estimate the non-productive green water use. It was found that the canopy and litter interception for *P. henkelii* was 29.8% and 6.2% respectively, while the modelled canopy and litter interception for *P. patula* was 22.1% and 10.7% respectively. If only the productive green water use (transpiration) is considered, then the water use efficiency of *P. henkelii* and *P. patula* was found to be 7.14 g.mm^{-1} and 25.21 g.mm^{-1} respectively. However, from a water management perspective it is important to consider the total green water use efficiency (transpiration + interception), which reveals a significantly lower water use efficiency of 3.8 g.mm^{-1} and 18.8 g.mm^{-1} for *P. henkelii* and *P. patula* respectively.

To extend the study to a globally relavent issue, the possible impact of climate change on canopy interception was investigated, as forests growth is critically linked to climate (*cf.* Chapter 7). To achieve this, the CABALA model was used to model LAI and transpiration of *Eucalyptus grandis* and *Pinus patula* under 9 different climate change scenarios, including changes in temperature, rainfall and

atmospheric CO_2. The simulated LAI values from the CABALA model for all 9 climate scenarios were then used to simulate canopy interception using the "variable storage Gash model". Results show that LAI may increase by as much as 24% and transpiration may decrease by as much as 13%, depending on the scenario, location and tree species. However, it was found that canopy interception does not change greatly, leading to the conclusion that under climate change conditions, canopy interception may not become a more dominant component of the hydrological cycle than it currently is as the changes under climate change are likely to be less than the natural variability from year to year. However, canopy interception remains an important consideration for water resources management and planning both currently and in the future.

ACKNOWLEDGEMENTS

PREFACE

The work described in this thesis was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from January 2008 to May 2011, under the supervision of Professor G. P. W. Jewitt.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

....
   Signature (Student)   Date
   Hartley Bulcock

....
  Signature (Supervisor)   Date
  Prof. G. P. W. Jewitt

DECLARATION 1 - PLAGIARISM

I, Hartley Hugh Bulcock declare that

1. The research reported in this dissertation, except where otherwise indicated, is my original work.

2. This dissertation has not been submitted for any degree or examination at any other university.

3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

    a. Their words have been re-written but the general information attributed to them has been referenced.

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Signed: …………………………………..

Hartley H. Bulcock

DECLARATION 2 – PUBLICATIONS

DETAILS OF CONTRIBUTION OF PUBLICATIONS that form part and/or include research presented in this dissertation (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication).

Publication 1 – Chapter 2

Bulcock, H.H. and Jewitt, G.P.W., in preparation. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands.

Research for this publication was conducted by H.H. Bulcock with technical advice from G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by G.P.W. Jewitt.

Publication 2 – Chapter 3

Bulcock, H.H. and Jewitt, G.P.W., in preparation. Modelling canopy and litter interception in commercial forest plantations in South Africa.

Research for this publication was conducted by H.H. Bulcock with technical advice from G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by G.P.W. Jewitt.

Publication 3 – Chapter 4

Bulcock, H.H., Kunz, R.P. and Jewitt, G.P.W., in preparation. National Estimates of Canopy interception using the Variable Storage Gash analytical interception model.

Research for this publication was conducted by H.H. Bulcock with technical advice from R.P Kunz and G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, graphs and map were produced by the same, unless otherwise referenced in the text of the paper. The model spreadsheet was created by H.H. Bulcock and then programmed by R.P. Kunz to be applied to all the quinary catchments containing forestry. The output from the program written by R.P. Kunz was used in generating the maps which were created by H.H. Bulcock. Editing and advice regarding data interpretation was provided by R.P. Kunz and G.P.W. Jewitt.

Publication 4 – Chapter 5

Bulcock, H.H., Gush, M.B. and Jewitt, G.P.W., in preparation. An investigation into the productive and non-productive green water-use of an indigenous *Podocarpus henkelii* stand in the KwaZulu-Natal Midlands.

Research for this publication was conducted by H.H. Bulcock with technical advice from M.B. Gush and G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, graphs and photos were produced by the same, unless otherwise referenced in the text of the paper. The tree growth data was supplied by M.B. Gush. Editing and advice regarding data interpretation was provided by G.P.W. Jewitt.

Publication 5 – Chapter 6

Bulcock, H.H. and Jewitt, G.P.W. 2010. Spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on canopy interception. *Hydrology and Earth System Sciences* 14: 383-392.

Research for this publication was conducted by H.H. Bulcock with technical advice from G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, graphs and maps were produced by the same, unless otherwise referenced in the text of the paper. The raw hyperspectral imagery was supplied by the CSIR, and processed by H.H. Bulcock. Editing and advice regarding data interpretation was provided by G.P.W. Jewitt.

Publication 6 – Chapter 7

Bulcock, H.H. and Jewitt, G.P.W., in preparation. An investigation into the impact of climate change on canopy interception and transpiration in commercial forests in South Africa

Research for this publication was conducted by H.H. Bulcock with technical advice from G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice regarding data interpretation was provided by G.P.W. Jewitt.

Publication 7 – Chapter 8

Bulcock, H.H. and Jewitt, G.P.W., in preparation. How do hydrological process studies improve our science: lessons from interception studies.

Research for this publication was conducted by H.H. Bulcock with advice from G.P.W. Jewitt. This publication was written in its entirety by H.H. Bulcock and all data tables, and graphs were produced by the same, unless otherwise referenced in the text of the paper. Editing and advice was provided by G.P.W. Jewitt.

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A	=	Available energy ($W.m^{-2}$)
a	=	Constant (-)
b	=	Exponent (-)
α	=	Curve shape parameter (cm^{-1})
c	=	Canopy cover fraction (-)
c_p	=	Specific heat capacity of air ($J.kg^{-1}.K^{-1}$)
ΔC	=	Change in canopy storage (mm)
ΔC_t	=	change in trunk storage (mm)
CO_2	=	Carbon Dioxide
D	=	Vapour pressure deficit (Pa)
ε	-	Light utilisation efficiency ($kg.C.MJ^{-1}$)
E	=	Evaporation rate ($mm.unit\ time^{-1}$)
λE	=	Latent Heat flux ($W.m^{-2}$)
E_I	=	Wet canopy evaporation ($mm.unit\ time^{-1}$)
E_p	=	Potential evapotranspiration ($mm.day^{-1}$)
E_{pl}	=	Potential plant transpiration ($mm.day^{-1}$)
E_T	=	Transpiration rate ($mm.unit\ time^{-1}$)
f_c	=	Crop coefficient (-)
f_g	=	Gap fraction of canopy (-)
f_i	=	Interception efficiency (-)
G	=	Soil heat flux ($W.m^{-2}$)
G	=	Annual net photosynthetic production (biomass) ($kg.\ C.\ m^{-2}.\ year^{-1}$) (Chapter 7)
γ	=	Psychrometric constant ($Pa.K^{-1}$)
γ	=	Rate of carbon loss a litterfall ($kg.C.kg^{-1}.DM.year^{-1}$) (Chapter 7)
h	=	height of cone (m) (Chapter 5)
h	=	Pressure head (m)
H	=	Sensible heat flux ($W.m^{-2}$)
I_l	=	Interception loss ($mm.day^{-1}$)
k	=	Extinction coefficient (-)
K(*h*)	=	Hydraulic conductivity ($mm.h^{-1}$)
K(*s*)	=	Saturated hydraulic conductivity ($mm.h^{-1}$)
λ	=	Latent heat of vaporisation ($J.kg^{-1}$)
LAI	=	Leaf area index (-)
m	=	Curve shape parameter (-)
n	=	Curve shape parameter (-)

n_c	=	Canopy N content (kg.N.m^{-2} ground)
p	=	Throughfall coefficient (-)
p_t	=	Stemflow coefficient (-)
P_g	=	Gross precipitation (mm)
P'_g	=	Rainfall needed to saturate canopy (mm)
ρ	=	Density of air (kg.m^{-3})
Q	=	Incident photosynthetically active radiation (MJ.m^{-2}.year^{-1}),
$Q\downarrow$	=	Global radiation (J.m^{-2}.day^{-1})
q	=	Drop retention number (-)
R	=	Intensity of gross precipitation (mm.unit time^{-1})
R	=	Annual respiration (kg.C. m^{-2}.year^{-1}) (Chapter 7)
r	=	Radius of the base of the cone (m)
$R(h)$	=	Root water uptake function dependant on pressure head
R_n	=	Net radiation (W.m^{-2})
R_m	=	Maintenance respiration cost of the plant (Chapter 7).
r_a	=	Aerodynamic resistance (s.m^{-1})
r_c	=	Canopy resistance (s.m^{-1})
r_c	=	Carbon used as a proportion of dry matter produced (Chapter 7)
r_0	=	Maintenance respiration rate per unit canopy N (kg.C.kg^{-1}.year^{-1}),
s	=	Slope of the saturated vapour pressure curve (Pa.K^{-1})
s	=	Specific leaf area (m^2.kg^{-1}.DM) (Chapter 7)
S_c	=	Canopy storage capacity (mm)
S_{ff}	=	Forest floor heat storage (W.m^{-2})
S_f	=	Stemflow (mm)
S_{cmax}	=	Maximum storage capacity (mm)
T	=	Throughfall (mm)
θ	=	Water content (cm^{-3}.cm^{-3})
θ_r	=	Residual water content (cm^{-3}.cm^{-3})
θ_s	=	Saturated water content (cm^{-3}.cm^{-3})
t	=	Time (seconds/hours/days)
V	=	Volume of cone (m^3)
v	=	Drop volume (mm^3)
v_e	=	Elemental volume (mm^3)
v_e^{max}	=	Maximum elemental volume (mm^3)
v_o	=	Mean volume of raindrop with zero kinetic energy (mm^3)
z	=	Height (m)

LIST OF ABBREVIATIONS

ACRU	=	Agricultural Catchment Research Unit model
BEEH	=	Bioresources Engineering and Environmental Hydrology
CABALA	=	Carbon Balance model
CSIR	=	Council for Scientific and Industrial Research
KZN	=	KwaZulu-Natal
MAP	=	Mean annual precipitation (mm.year^{-1})
NDVI	=	Normalized difference vegetation index
NIR	=	Near infrared
PAR	=	Photosynthetically active radiation
Q_nC	=	Quinary catchment
RMSE	=	Root mean square error
SAVI	=	Soil adjusted vegetation index
SVAT	=	Soil-vegetation-atmosphere transfer
SWIF	=	Soil water in forests
UKZN	=	University of KwaZulu-Natal
VOG1	=	Vogelman Index 1
WRC	=	Water Research Commission

CHAPTER ONE

Introduction and Literature Review

1.   INTRODUCTION

Interception is one of the most underrated and underestimated processes in rainfall-runoff analysis. Some models disregard it completely, based on the argument that it is generally a small portion of the total evaporation (Savenije, 2004). However, Beven (2001) highlighted that evaporation from intercepted precipitation on leaf surfaces in rough canopies can be very efficient and a significant component of the total water balance in some environments. In a forest with a closed canopy, the interception of precipitation is a major component of the influence that forests exert on the hydrological cycle (Jewitt, 2005) and may be defined as the difference between gross rainfall and net rainfall (net rainfall being the sum of stemflow and throughfall). Throughfall is the water that falls to the ground either directly through gaps in the canopy, or indirectly by having dripped off leaves, stems and branches. The amount of direct throughfall is controlled by the extent of canopy coverage. The remaining water that is retained on the leaves is then evaporated from the wet canopy surface. A broader definition (Savenjie, 2004) is that interception accounts for the part of the rainfall that is captured before it can take part in the subsequent runoff and sub-surface processes. This definition is more useful for rainfall-runoff analysis and linked hydrological modelling, where the main interest is surface runoff, the soil moisture budget, transpiration, recharge and ground water processes.

To a hydrologist or water resources planner who is ultimately interested in the amount of water flowing down a river, the vegetation canopy is a barrier for precipitation to cross before reaching the soil and possibly making its way to the river (Davie, 2003). Water stored in forest canopies has been found to evaporate at rates in excess of available net radiation and potential evaporation because of advection and the low aerodynamic resistance of wet canopies (David *et al.,* 2005). To those interested in earth atmosphere interactions, vegetation creates a "blurred" surface for evaporation to occur from (Davie, 2003). When one considers both viewpoints, it is not surprising that interception is often not perceived as a separate process within the hydrological cycle. Some authors consider interception as a "flux" (Gerrits *et al.,* 2006), but interception will be referred to as a "loss" in this document.

From a South African perspective, Dye (1993) suggests that the problem with using international interception values where interception loss from forests is a significant component ($25 - 75\%$) of total evaporation (David *et al.,* 2005), is that the published findings are difficult to assess and adapt to local needs because;

a) interception depends on the relative frequency of different rainfall classes, with frequent occurrences of small rainfall events resulting in larger total values of interception losses,

b) evaporation during rainfall is an important component of interception loss, and

c) comparisons of interception loss between sites where climate differs are difficult.

In South Africa, commercial forestry plantations of *Eucalyptus*, *Pinus*, and *Acacia* genera form the bulk of the feedstock for the country's timber industry. Summerton (1995) noted that in general, interception loss (I_l) by *Pinus* species is greater than that of *Eucalyptus*, *Acacia mearnsii* and short vegetation (e.g. grassland), in that order. Pine canopies are assumed to intercept more water than eucalypt canopies due to their larger leaf area index (LAI), and the fact that water clings to pine needles as opposed to being repelled in the case of eucalypts (Summerton, 1995). Studies by several authors have shown that large variations in I_l exist under different climatic conditions. I_l is often cited in the literature as a percentage of gross precipitation (P_g), as shown in Table 1.1.

Table 1.1   Values of canopy interception as a percentage of gross precipitation

I_L (% Pg)	Details	Country	Reference
23.3%	*Eucalyptus regnans*	Australia	Langford and O'Shaughnessy (1978)
15.0%	*Eucalyptus obliqua*	Australia	Feller (1981)
6 %	*Eucalyptus grandis*, 4 years old	South Africa	Dye (1993)
14%	*Eucalyptus radiata, E. dalrympleana, E. pauciflora*	Australia	Talsma and Gardner (1986)
11.4%	*Eucalyptus globulus*	Australia	Crockford and Richardson (1990)
20–40%	Pines	United Kingdom	Rutter *et al*., (1971)
10-35%	*Pinus taeda*, 15 years old, unthinned, with 85 % canopy closure	U.S.A	McCarthy *et al*., (1991)
5-25%	*Pinus taeda*, 15 years old, thinned, with 50 % canopy closure	U.S.A	McCarthy *et al*., (1991)
19%	*Pinus radiata*, seven years old	New Zealand	Kelliher *et al*., (1992)
13%	*Pinus patula,* 10 years olds.	South Africa	Versfeld and Dye (1992)
20%	*Pinus radiata,* 29 years old	South Africa	Versfeld (1987)
38.1%	*Pinus elliottii*	Australia	Johansen (1964)
13.0%	*Acacia aneura*	Australia	Pressland (1973)
15.2	*Acacia harpophylla 15.2*	Australia	Tunstall (1973)
>20%	*Acacia mearnsii*	South Africa	Everson *et al*., (2006)
25%	*Acacia mearnsii*	India	Samraj *et al*., (1982)
20-40%	Temperate Forest	U.S.A	Zinke (1967)

A smaller, although significant role is played by evaporation from the forest floor. However, in some cases half or more of the total forest evapotranspiration originates from the forest floor evaporation process (Schaap and Bouten, 1997). According to Gerrits *et al.*, (2007) interception measurement studies have generally concentrated on canopy interception, whereas interception by the understorey and forest floor can be as high or even higher. In this study, the results from measured and modelled canopy interception discussed in Chapters 3 and 4 of this document, showed canopy interception to be as high as between 14.9% and 27.7% of gross precipitation. The litter interception was found to be between approximately 6.6% and 12.1 % of gross precipitation.

Interception loss from forests depends on the atmospheric conditions that drive evaporation and rainfall characteristics, but also the nature and density of the forest stand. In commercial forests this usually depends on the management practice and the age of the trees, as older trees typically have denser canopies and correspondingly higher canopy storage, and higher interception loss than younger trees (Jewitt, 2005). A study by Kuczera (1987) on *Eucalyptus* forests in Australia showed the relationship between interception loss as a percentage of gross precipitation and tree age as illustrated in Figure 1.1. Kuczera (1987) found that the interception loss increased with age until a threshold was reached at approximately 30 years. Thereafter there was a gradual decrease in the interception loss.
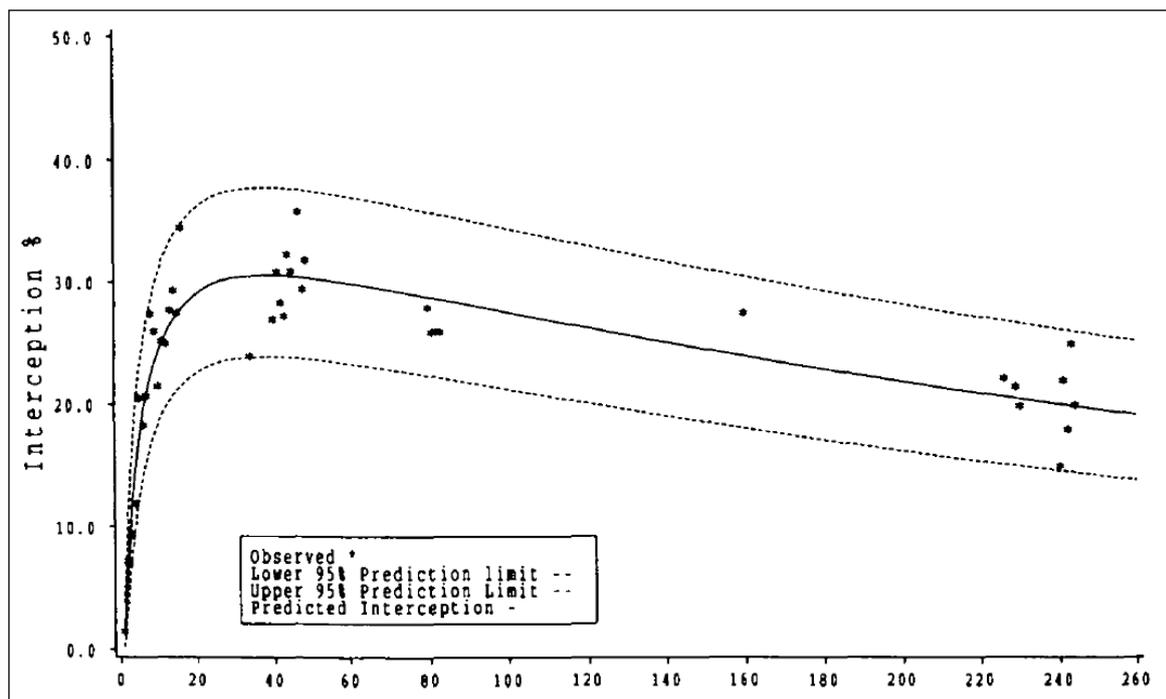
Figure 1.1   The relationship between interception loss as a percentage of gross precipitation and tree age (After: Kuczera, 1987).

Various South African researchers, including Schulze *et al.*, (1978); Dye and Versfeld, (1992); and Versfeld and Dye, (1992), have highlighted that canopy interception ranges from 0.5 to 3.5 mm per rainfall event in *Pinus* species. Pitman (1973) argued that interception in southern Africa can be as

much as 8 mm.day^{-1}, while Savenjie (2004) suggests that 2 to 5 mm.day^{-1} is appropriate, depending on the land use. Interception is a threshold process, as a certain amount of precipitation is required before successive processes can take place. An error introduced in analysing and modelling interception, especially disregarding it will automatically introduce errors in the modelling of subsequent processes. Therefore, representing interception accurately is important for water resources modelling and planning. Using the "variable storage Gash model" (*cf*. Chapter 4) to model the canopy interception for the three main forestry genera in South Africa, viz., *Eucalyptus, Pinus* and *Acacia*, it was found that on average between 1.0 and 3.0 mm.day^{-1} was intercepted for rainy days.

Methods to quantify canopy interception typically require LAI as an input into the various equations and process models. The use of remote sensing technology has become an increasingly important tool to estimate LAI for use in modelling/estimating canopy interception (*cf*. Chapter 7). The ability to remotely predict LAI and to use this to estimate water use over a large area is sought after by various stakeholders in the forestry industry, as well as water resources managers and planners. Due to the future availability and accessibility of hyperspectral sensors in southern Africa there is likely to be an increased interest in using high spectral resolution data for a wide variety of environmental applications.

Although interception may contribute a relatively small contribution to total evaporation in some situations, in a semi-arid environment, any reduction in surface or groundwater flows which affects water supply for domestic, agricultural and environmental purposes is considered significant (Hall *et al*., 1992). It is therefore important to consider interception loss as an important part of the hydrological cycle. In forested areas, this may be of particular importance and one therefore needs to closely examine the partitioning of rainfall in such environments.

1.1 Aims and Objectives

The overall aim of this study was to improve the knowledge and perceptions of the impact and quantity of canopy and litter interception in commercial and indigenous forests in South Africa.

The objectives of this study relating to canopy and litter interception are as follows:
  a) Measure and quantify canopy and litter interception by the three main commercial forestry genera in South Africa as well as an indigenous *Podocarpus henkelli* forest.
  b) To develop and improve canopy and litter interception models that are able to utilise readily available data and as few parameters as possible.
  c) To verify the models from the *in situ* field measurements undertaken during the study period.
  d) To upscale the application of the canopy interception model to a national scale.

e) To assess the use of remote sensing to determine LAI as an aid in estimating canopy storage capacity and canopy interception.

f) To apply tools/models to assess the potential impact of climate change on canopy interception in South Africa.

1.2   Thesis Structure

The format of this dissertation includes a literature review and seven "publishable" papers. As shown in Figure 1.2, the first paper provides some philosophical thoughts on the importance of field studies to better understand hydrological processes such as canopy and litter interception. In this thesis, the term "forest" refers to both natural forests and planted commercial plantations. The second paper discusses the field data collection and analysis. In the third paper the rationale and development of canopy and litter interception models that make use of easily obtainable parameters and their verification using the data collected and described in paper two are explained. The fourth paper provides a description of the application of the "variable storage Gash" canopy interception model detailed in paper three to all the quinary catchments in South Africa that contain forestry and provides national results. The fifth paper considers the components of total evaporation including transpiration and canopy and litter interception in an indigenous *Podocarpus henkelii* stand. The sixth paper details the use of hyperspectral remote sensing to estimate leaf area index, canopy storage capacity and canopy interception in a South African research catchment (i.e. the Two Streams catchment). The seventh paper considers the impact of climate change on the two dominant forest hydrological processes, namely transpiration and canopy interception. Some overlap may exist between the seven papers as they are intended to be submitted to different journal publications.

Figure 1.2 illustrates the structure and links of the thesis under the four broad headings of introduction, field studies, applications and synthesis. The scale at which the research was undertaken or could be undertaken is detailed in the legend.
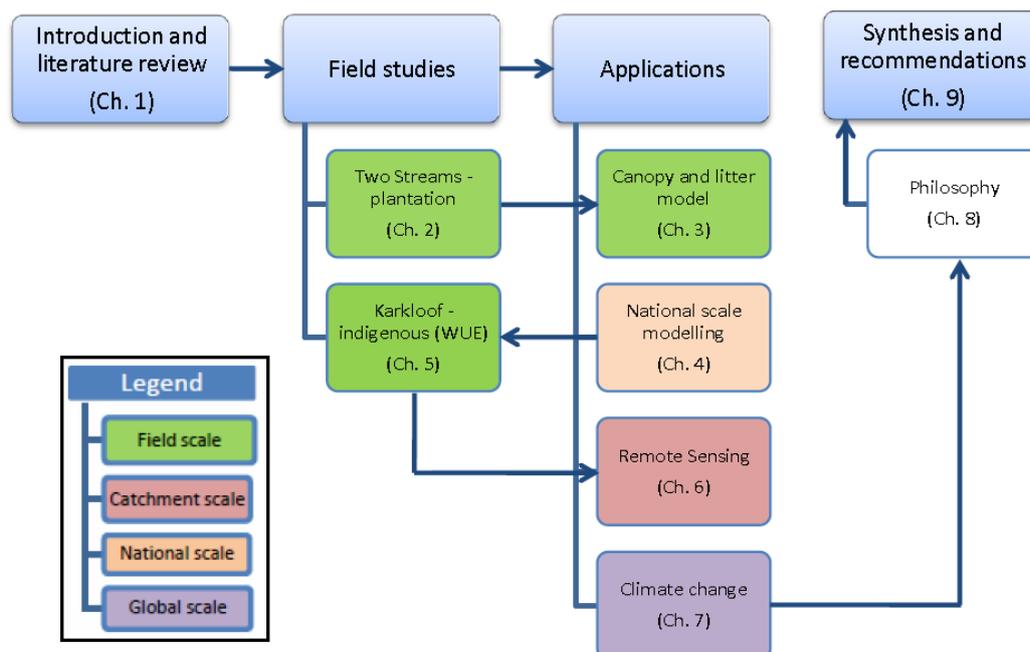
Figure 1.2   Flow diagram of the structure of the thesis.

2.   PARTITIONING OF PRECIPITATION IN FORESTS

In forest hydrology, some interpretations highlight three main rainfall partitioning points of the hydrological cycle, as illustrated in Figure 1.3 (Jewitt, 2005). These three partitioning points are not only applicable at the scale of a forest, but apply to the whole catchment, as illustrated in Figure 1.4 (Ward and Robinson, 1990). The first point is at the canopy level, where incoming precipitation is partitioned into vertically orientated fluxes. In the upward direction these fluxes are represented by evaporating water (canopy interception loss and transpiration from stomata), and in the downward direction represented by throughfall, stemflow and canopy drip, which ultimately forms net precipitation once passing through the litter layer (Veen and Dolman, 1989; Jewitt, 2005).

The second partitioning point is at the soil surface where the net precipitation is partitioned both horizontally and vertically. The horizontal partitioning is due to runoff and vertically due to infiltration (Veen and Dolman, 1989; Jewitt, 2005). Litter interception could also be considered at this partitioning point as an upwards flux.

The third partitioning point is in the root zone where upward fluxes are generated. This is as direct evaporation from the soil surface, but more significant is the uptake of water by the root system for transpiration. As with the second partitioning point at the soil surface, there is also horizontal and vertical partitioning in the root zone. The downward percolation of water, which ultimately recharges the groundwater (Veen and Dolman, 1989; Jewitt, 2005) and capillary rise provide the vertical component and horizontally as interflow and throughflow (Ward and Robinson, 1990; Jewitt, 2005), provided by unsaturated flow that moves downslope to eventually become streamflow.
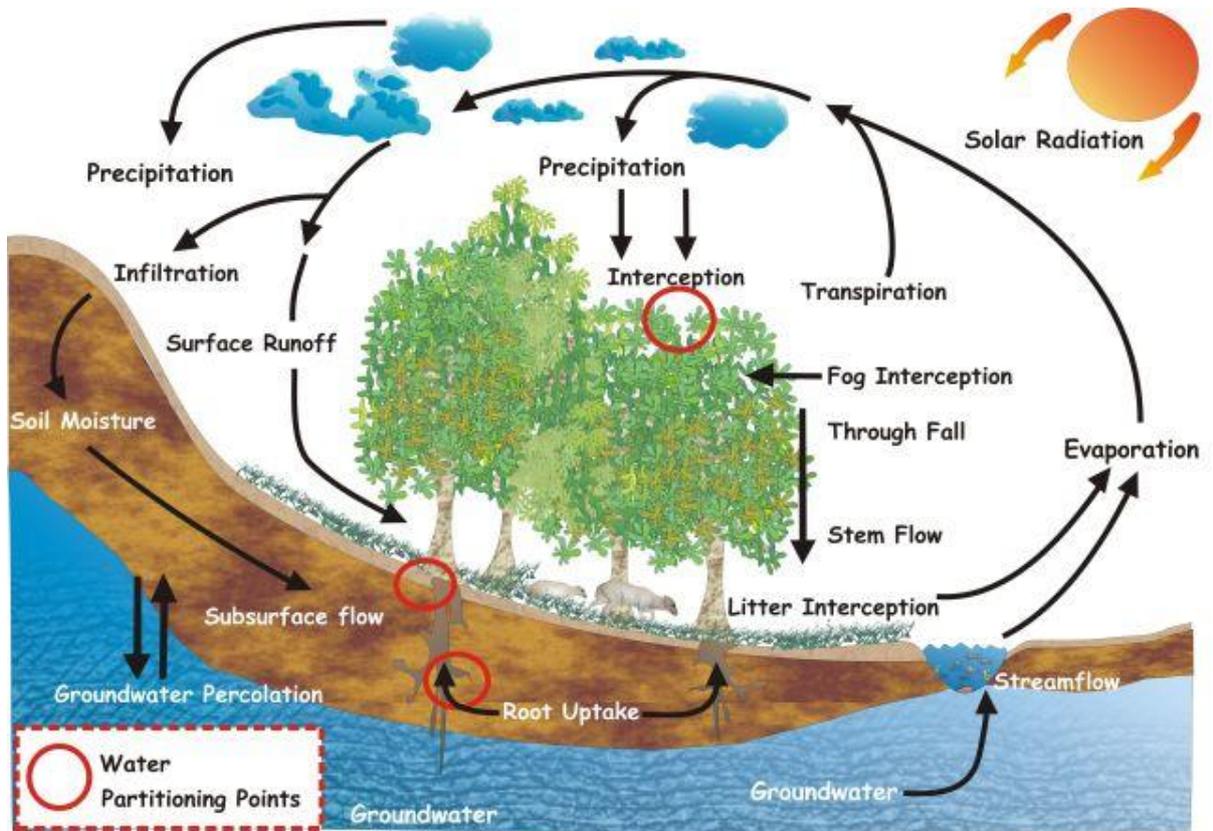
Figure 1.3   The key partitioning points in the forest hydrology cycle (After: Jewitt, 2005).
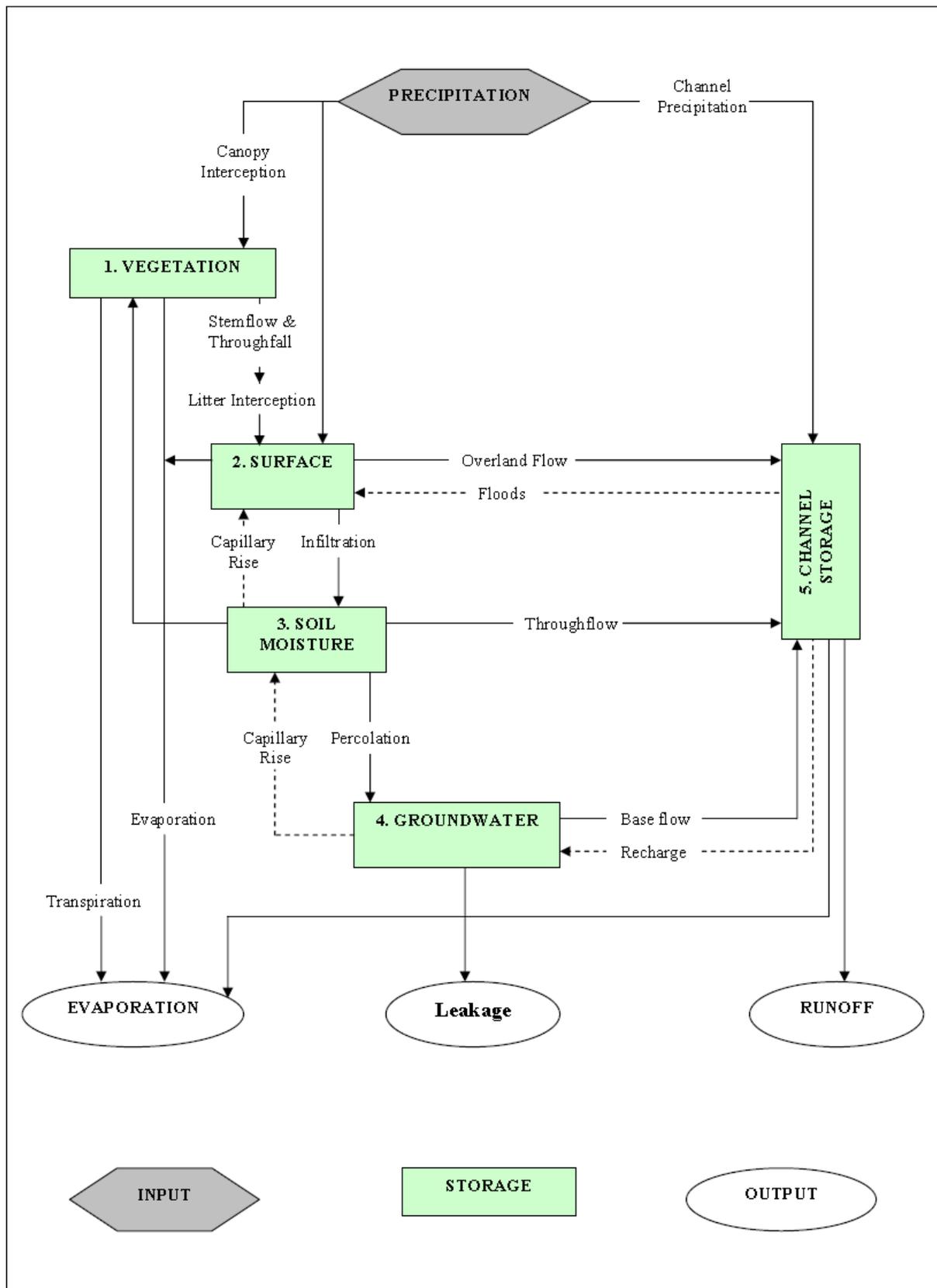
Figure 1.4   The catchment hydrological system (Adapted from: Ward and Robinson, 1990).

3.   WOOD VERSUS WATER: A SOUTH AFRICAN PERSPECTIVE

South Africa is a semi-arid and water scarce country, but is the largest industrial roundwood producer in Africa (Jacobsen, 2003). It is however, poorly endowed with natural forests and is therefore heavily dependent on plantations of exotic forestry species to meet its timber requirements (Dye and Versfeld, 2007). In 2007, Forestry South Africa (Godsmark, 2008) estimated that approximately 1.1% of South Africa was under plantation forestry, an area of 1 351 402 ha, the majority of which is located in the higher-rainfall eastern and southern regions of the country. These plantations comprise of 53.5% pine, 37.7% eucalypts, 8.1% wattle and 0.7% 'other'. Forestry contributes substantially to South Africa's economy, with the formal forestry sector contributing 2% to the national Gross Domestic Product (GDP) (Godsmark, 2008).

3.1   Legislation

A severe drought in South Africa in 1960 focussed existing concerns regarding the impact of commercial forestry on water resources. Concerns for the protection of South Africa's water resources resulted in the formation of investigative committees which eventually led to the legislative control of afforestation and forestry practices. The outcome was an amendment to the Forest Act (Act 72 of 1968), which required timber growers to apply for permits to establish new commercial plantations (DWAF, 2007). As a response, in 1972 an afforestation permit system (APS) was introduced. Major catchments in the country were classified into three categories according to allowable reductions in streamflow based on downstream demand. Class 1 catchments were not allowed any further reduction below the mean annual runoff (MAR) before 1972. Class 2 and 3 were allowed a further 5% and 10% reduction in MAR respectively (Van der Zel, 1995).

The National Water Act of 1956 was replaced by a "new" National Water Act in 1998 (NWA, Act 36 of 1998). The way in which water is viewed has been changed in the NWA with the guiding principles being clearly stated as Equity, Sustainability and Efficiency, recognising "…*the basic human needs of present and future generations, the need to promote social and economic development through the use of water resources, and the need to establish suitable institutions in order to achieve the purposes of the Act*" (preamble of NWA, Act 36 of 1998).

In Chapter 4 of the NWA (Act 36 of 1998), the various permissible uses of water in terms of licensed and unlicensed entitlements are explained. This chapter includes, amongst other uses, activities that reduce streamflow. Commercial forestry has been deemed to be a Streamflow Reduction Activity (SFRA), requiring any new forestry development to be licensed in common with several other forms

of water use. Established plantations had to have their water use registered through the water use registration process and if deemed lawful will be issued with a SFRA licence (DWAF, 2007).

An SFRA is defined in Chapter 4, Part 4, Section 36(1) of the NWA as:
The use of land for afforestation which has been or is being established for commercial purposes; and an activity which has been declared as such under subsection (2), which states:

"*The Minister may, by notice in the Gazette, in relation to a particular area specified in that notice, declare any activity (including the cultivation of any particular crop or other vegetation) to be a streamflow reduction activity if that activity is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly*" (NWA Section 36(2)).

As forestry has been declared a SFRA, it is therefore important to understand all forest processes that influence the amount of water reaching the stream. One such process that has not received enough attention in South Africa is canopy and litter interception, as highlighted in the following section.

4.   CANOPY INTERCEPTION

"*Evaluating the quantitative importance of canopy interception loss is an important consideration especially in semi-arid regions where soil moisture is a limiting factor influencing plant productivity, and where runoff and groundwater recharge are essential for meeting agricultural, industrial, and residential water demands*" (Carlyle-Moses, 2004, pp.182)

4.1   Canopy Interception and the Water Balance

Rainfall interception plays an important role both in the water balance of a catchment and in the ecology of the vegetation (David *et al.*, 2005). Calder (1990) in Savenije (2004) defines interception as the difference between rainfall and throughfall. Savenije (2004) however adds that if evaporation from interception is defined as the fast feedback to the atmosphere within the space of about one day of the rainfall that does not reach the root-zone or drainage system, then interception counts for more. As noted in Section 1, a broader definition is that, interception accounts for the part of the rainfall that is captured before it can take part in the subsequent runoff and subsurface processes.

Many hydrological models disregard or underestimate interception, leading to poor model performance (Gerrits *et al*., 2008), despite it being considered by Savenije (2004) as one of the most important processes in hydrological modelling. Interception is a threshold process as a certain amount of water is needed before successive processes such as infiltration or runoff can occur (Gerrits *et al*., 2008). Therefore, an error introduced in modelling interception (especially disregarding it) will automatically introduce errors in the calibration of subsequent processes (Savenije, 2004).

According to Ward and Robinson (1990), interception can be categorised into three classes; i.e. where it has a neutral, a negative or a positive effect on the catchment water balance.

The neutral hypothesis assumes that interception losses are essentially evaporative losses and that only a certain amount of energy is available in any period of time that can be used to evaporate water from within the leaf (transpiration) or to evaporate water from the surface of the leaf (interception loss). Burgy and Pomeroy (1953) and McMillan and Burgy (1960) in Ward and Robinson (1990) concluded that wet foliage evaporation was equally balanced by a reduction in transpiration loss, so the net interception loss is zero. In such cases, interception loss is considered to be an alternative to, and not an addition to transpiration, and would therefore have little, if any effect on the catchment water balance. This hypothesis was given additional credibility through its apparent support by Penman (1963) who affirmed that "…the same energy cannot be used twice, and while the intercepted water is being evaporated the drain on the soil water is checked".

The negative hypothesis regards interception as a loss of precipitation that would otherwise have been available for soil evaporation, for infiltration through the surface, or for overland flow (Ward and Robinson, 1990). Whitmore (1961) in Ward and Robinson (1990) suggested that in South Africa, interception probably accounts for between 5-15% of the annual rainfall. For many years there had been controversy about whether evaporation from a wetted surface could take place at a higher rate than the evaporation and transpiration from unwetted vegetation and therefore result in a net loss for the water balance. During the 1960's evidence was accumulated that supported the conclusion that intercepted water evaporates much faster than transpired water and, therefore much of the interception loss represents an additional loss to the catchment (Ward and Robinson, 1990). This hypothesis is best described by considering the Penman-Monteith (1965) equation, Equation 1.1, which is considered to be the most realistic description of evaporation from canopies.

$$\lambda E_T = \frac{sA + \rho.c_p.D/r_a}{s + \gamma(1 + r_c/r_a)} \tag{1.1}$$

Where, E_T is the transpiration rate, A is the available energy (W.m^{-2}), c_p is the specific heat capacity of air (J.kg^{-1}.K^{-1}), D is the vapour pressure deficit (Pa), γ is a psychrometric constant (Pa.K^{-1}), λ is the latent heat of vaporisation (J.kg^{-1}), ρ is the density of air (kg.m^{-3}), s is the slope of the saturated vapour pressure curve (Pa.K^{-1}), r_a is the aerodynamic resistance (s.m^{-1}), and r_c is the canopy resistance (s.m^{-1}).

When the canopy is wetted, evaporation of intercepted rainfall is largely a physical process that does not depend on the functioning of the stomata. The evaporation rate from a wet canopy (λE_I) can therefore be expressed as Equation 1.2 with $r_c = 0$.

$$\lambda E_I = \frac{sA + \rho.c_p.D/r_a}{s + \gamma} \tag{1.2}$$

Therefore, for a given temperature, the rate of evaporation of intercepted rainfall depends on: the available energy (A), vapour pressure deficit (D), and the aerodynamic resistance (r_a). The aerodynamic resistance to water vapour transfer is a function of the roughness of the evaporative surface and the wind speed (Monteith and Unsworth, 1990).

The controversy can be clarified by defining a 'relative interception rate' (Equation 1.3) by dividing the Penman-Monteith equation for a wet canopy (Equation 1.2) by the equation for a dry canopy (Equation 1.1).

$$\frac{E_I}{E_T} = 1 + \frac{\gamma}{s + \gamma}\left(\frac{r_c}{r_a}\right) \tag{1.3}$$

The relationship between E_I/E_T and r_c/r_a is illustrated in Figure 1.5. From this it can be seen that when r_c and r_a are more or less the same (i.e. $r_c/r_a \approx 1$), as with short vegetation, the rate of evaporation of intercepted water is about the same as the transpiration rate. However, when r_a is an order of magnitude less than r_c (i.e. $r_c/r_a \approx 10$), as is the case for forests, intercepted water evaporates at 3 to 5 times the transpiration rate (David *et al.*, 2005).
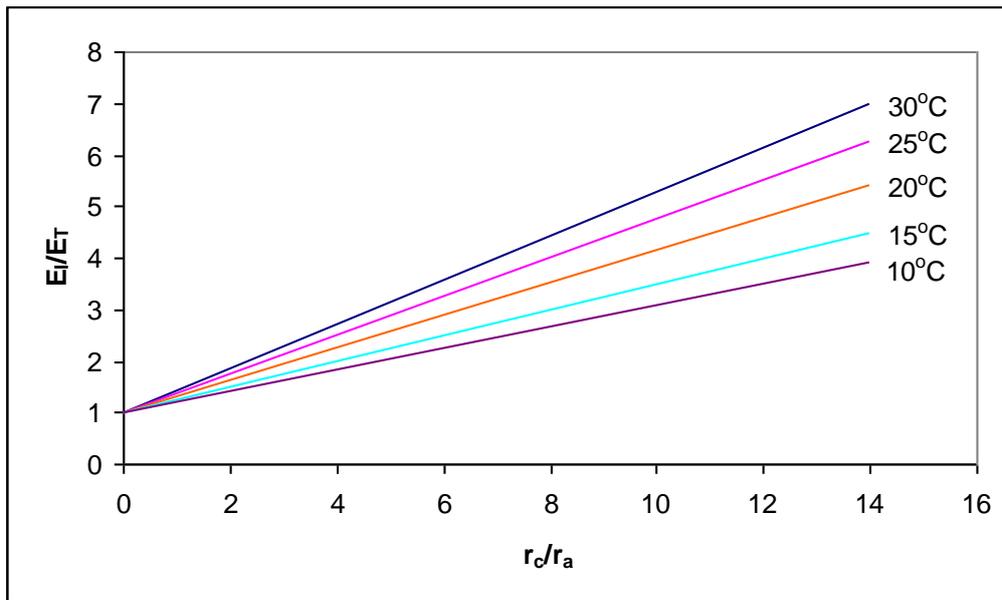
Figure 1.5   Change of relative interception rate E_I/E_T with the ratio r_c/r_a and temperature (David *et al.*, 2005).

The evaporation from a wet canopy is therefore a net loss for a catchment containing forest, but not for short vegetation. The neutral hypothesis is therefore applicable to short vegetation only.

The positive hypothesis views the role of interception in certain circumstances where the interaction of water loss and gain in vertical and horizontal interception results in a net gain of water in the catchment. This is most likely to occur in mountainous or upland areas of high relief, where fog and low cloud is frequent or persistent, particularly where wind-driven cloud intersects directly with the surface (Ward and Robinson, 1990; Hamilton, 2008). Cloud or fog forests are most likely to be found on large mountain ranges in the interior, at elevations between 2000 m and 3000 m. On coastal ranges, they can occur at about 1200m (Hamilton, 2008). Transpiration in these areas is also relatively low.

4.2   Factors Affecting Canopy Interception

In order to estimate/predict interception loss, one needs to understand the factors that affect interception. The development of interception models are discussed in Section 4.3. Canopy water fluxes such as interception and throughfall (i.e. the amount of precipitation reaching the soil surface) are affected by the forest type, ground cover, and climatic conditions (Crockford and Richardson, 2000). Crockford and Richardson (2000) consider three partitioning points in forest hydrology, but neglect to include the forest floor litter as one. Therefore, a better approach is to partition precipitation into four fractions;

1. that which remains on the vegetation and is evaporated during or after the rainfall event (canopy interception),
2. that which remains on the forest floor litter and is evaporated during or after the rainfall event (litter interception),
3. that which flows to the ground via the trunk or stem of the plant (stemflow), and
4. the rainfall that may or may not come into contact with the canopy and which falls to the ground between the various components of the vegetation (direct throughfall).

4.2.1   Climatic parameters

Climatic factors play a vital role in the determination of the amount of water that is intercepted. In most areas of the world there are large variations in the features of rainfall within and between seasons. These climatic conditions are important both during and after the event (Llorens *et al.*, 1997). Evaporation during the event may comprise a substantial proportion of the total amount of water evaporated (Crockford and Richardson, 1990; 2000). The climatic factors that affect interception are;

1. Amount, intensity, and duration of rainfall,
2. Rainfall sequence,
3. Solar radiation,
4. Wind speed and direction during and after the events,
5. The air temperature, and
6. Humidity.

High intensity rainfall of short duration yields lower interception values than low intensity events of long duration. Discontinuous events also aid in yielding higher interception values.

4.2.2   Canopy storage capacity

Canopy storage capacity changes through the season, although in most models it is usually considered as a constant parameter for a given vegetation cover. The concept of canopy storage capacity was initiated by Horton (1919). Water is retained on the surface of leaves, twigs, and branches by surface tension until the surface tension forces are in balance with the gravitational forces (Leonard, 1967 in David *et al.*, 2005). Once the canopy reaches its storage capacity (S), dripping will start, although not completely sequential and simplistic as direct throughfall may also occur. Storage capacity can then be defined as the minimum amount of water necessary to completely cover the canopy surface in still air. The storage capacity can be related to the LAI, which is a primary variable for estimating canopy interception, and has been incorporated into the revised version of Gash's model by Van Dijk and Bruijnzeel (2001a, 2001b) to allow it to be applied to rapidly growing vegetation where the LAI is changing through time. It also depends on the hydrophobicity (water repellency) of leaves, as well as their angle of orientation.

4.2.3   Throughfall and stemflow

Precipitation reaches the forest floor via two main pathways. Firstly by throughfall, and secondly by stemflow (Abdenbi and Rapp, 1997), which combined is termed net precipitation (Chang, 2006). Throughfall is very variable among forests as well as within a forest and its accurate measurement and estimation is often difficult. Typically, throughfall has a high spatial variability with dripping concentrated mainly at the edges of the crown (David *et al.*, 2005). In a study by Carlyle-Moses (2004) in north-eastern Mexico, a strong positive correlation ($r^2 = 0.999$) between throughfall depth (mm) and gross precipitation depth (mm) was found in a matorral subinerme-spineless brush community under wet season conditions (Figure 1.6). In the same study, it was found that there is a curvilinear relationship between gross precipitation partitioned into throughfall and gross precipitation depth (mm) (Figure 1.7). Often little attention is paid to stemflow. In fact stemflow is often not measured at all. According to Chang (2006), for most species, about 2 to 5% of precipitation flows to the ground along stems. Although stemflow may be a small quantity, it may be of ecological importance because the rainwater flows directly into the rooting zone of the tree (Chang, 2006).
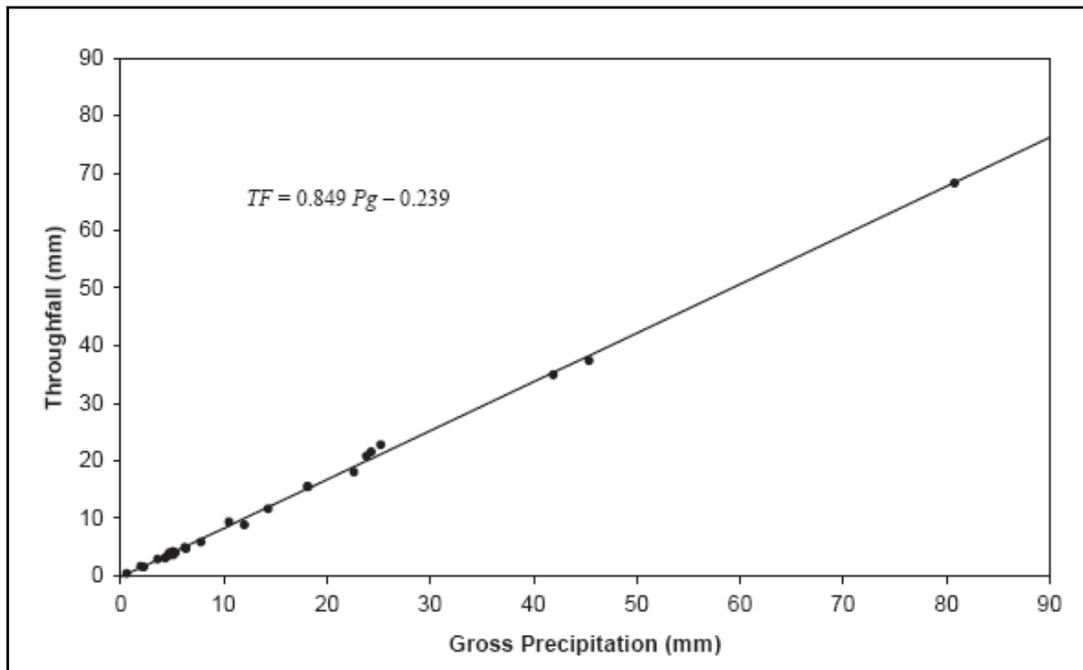
Figure 1.6　　Throughfall depth (mm) as a function of gross precipitation depth (mm) in a matorral subinerme – spineless brush community in north-east Mexico (After: Carlyle-Moses, 2004).
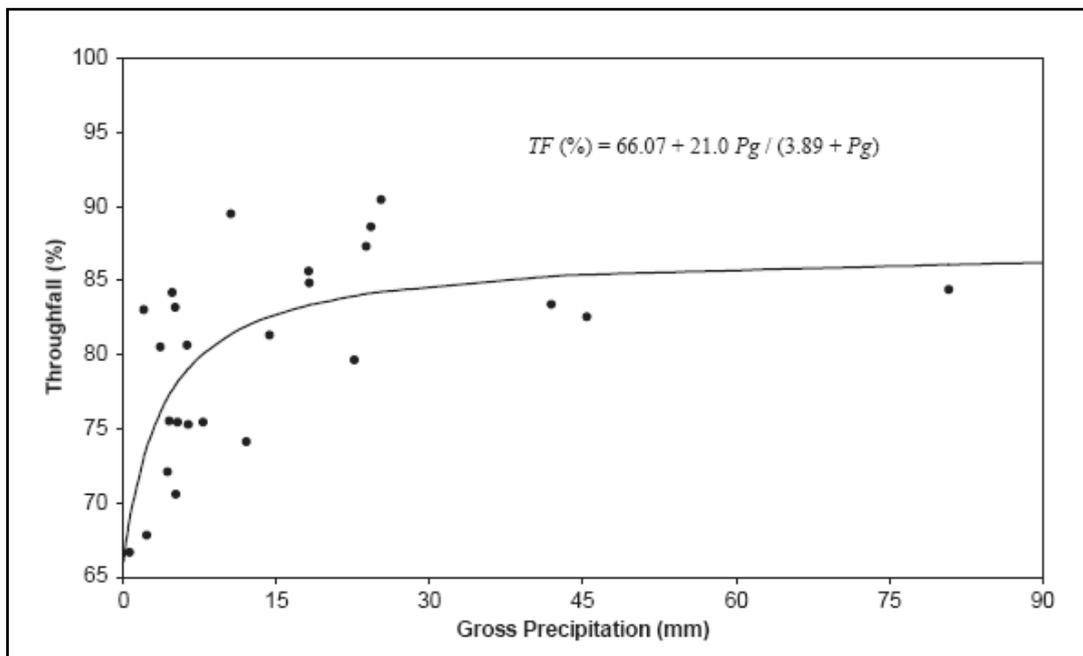
Figure 1.7　　Throughfall as a percentage of gross precipitation in a matorral subinerme – spineless brush community in north-east Mexico (After: Carlyle-Moses, 2004).

According to Crockford and Richardson (2000), stemflow and throughfall can be characterised by the following tree characteristics:

1. **Crown size**. Trees with larger crowns for a given trunk Diameter at Breast Height (DBH) have a higher potential for high stemflow yields.

2. **Leaf shape and orientation**. Trees that have their leaves orientated at an angle above the horizontal (i.e. the leaf tip is above the petiole) and have a concave shape may have larger stemflow yields, as water landing on the leaves is channelled to the branches. Conversely, trees with vertical or near vertical leaf orientation have lower stemflow yields as their only contribution to stemflow is when leaf drips land on the branches.

3. **Branch angle**. Branches at steep angles have a greater potential for contributing to stemflow than more horizontal or near horizontal branches which do not contribute to stemflow. This angle effect also applies to smaller twigs and branches.

4. **Bark type**. The thickness and bark type varies greatly between species for trees of similar size. The wettabilty and thickness of the bark has a substantial effect on stemflow yield. Bark that is smooth and easily wet has a potential for high yields whereas thick and absorptive bark will result in much lower yields of stemflow. Only once the thick and absorptive bark is saturated will stemflow commence.

5. **Canopy gaps**. Stemflow is also affected by the gaps in the canopy. This is because trees with larger gaps allow greater access for the rain to make contact with the trunk. The gaps in the canopy will also affect the amount of throughfall that is permitted.

Crockford and Richardson (1990; 2000) also describe the rainfall characteristics that affect stemflow yields. The continuity and proportion of rainfall events may be such that there are no, or very few, rainless periods. They may also be multiperiod events during which the rainless periods vary in number and size. The length and frequency of the dry periods, coupled with air temperature, wind run, and relative humidity influence stemflow (i.e. the greater the evaporation, the lower the stemflow yield). Therefore, dry periods in winter do not reduce stemflow as much as similar periods in summer (Crockford and Richardson, 1990; 2000). High intensity rainfall may produce branch flow that exceeds the capacity of the flow path and drip may occur. This results in the stemflow yield being lower than for events of similar magnitude and lower intensity. The angle of the rainfall is of particular importance in sparse canopies because lower angle (to the horizontal) facilitates the commencement of stemflow when only one side of the trunk is wet. This is particularly noticeable in species with thick and absorptive bark (Crockford and Richardson, 1990; 2000).

4.3   Canopy Interception Models: From Origin to State-of-the-Art.

The first reference to the development of canopy interception models in current literature can be ascribed to Horton (1919) who defined interception loss as "leaf storage capacity and evaporation loss during the storm" which he expressed as:

$$I_l = \mathrm{E}dt + \mathrm{S_c} \qquad\qquad (1.4)$$

Where:

$\quad$ E = $\quad$ evaporation rate of intercepted water during rainfall,

$\quad$ $\mathrm{S_c}$ = $\quad$ canopy storage capacity, and

$\quad$ t = $\quad$ rainfall duration.

Until the early 1970's, attempts to generalise interception losses were usually expressed in the form of regression analyses of interception loss and bulk rainfall (Llorens, 1997).

Rutter *et al.*, (1971, 1975) were the first to model forest rainfall interception with a physically based model using hourly rainfall and meteorological data (Llorens, 1997), having recognised that the process was primarily driven by evaporation from the wetted canopy. In a review of interception models done by Muzylo *et al.*, (2009), they found that up to March 2008, the Rutter model had been used in 42 published papers. The evaporation from the wet canopy is calculated using the Penman-Monteith equation with the canopy resistance set as zero (Rutter, 1971). The canopy structure is described by the throughfall coefficient (p), the stemflow partitioning coefficient (p_t), the canopy storage (S_c) and the trunk storage (S_t). The throughfall, stemflow and interception loss is estimated in the model using input rainfall and meteorological data (Rutter, 1971; Valente *et al.*, 1997) and is illustrated in Figure 1.8. The model is essentially based on the dynamic calculation of the water balance of the canopy and trunk through Equations 1.5 and 1.6.

$$(1 - p - p_t)\int P dt = \int D dt + \int E dt + \Delta C \qquad\qquad (1.5)$$

$$p_t \int R dt = Sf + \int E_t dt + \Delta C_t \qquad\qquad (1.6)$$

Where R is the intensity of gross rainfall, D is the rate of drainage from the canopy, E is the rate of evaporation of water intercepted by the canopy, ΔC is the change in canopy storage, Sf is stemflow, E_t is the evaporation of water intercepted by the trunk, and ΔC_t is the change in trunk storage.

Canopy Evaporation
E

Trunk Evaporation
E_t

Gross Rainfall
R

Canopy Input
$(1-p-p_t)R$

Free Throughfall
pR

Trunk Input
p_tR

$$E = \begin{cases} E_p \dfrac{C}{S}, & C < S \\ \text{or} \\ E_p, & C \geq S \end{cases}$$

$$E = \begin{cases} \varepsilon E_p \dfrac{C_t}{S_t}, & C_t < S_t \\ \text{or} \\ \varepsilon E_p, & C_t \geq S_t \end{cases}$$

C

S

S_t

C_t

Canopy Drainage
$D = D_t exp[b(C-S)]$

Throughfall

Stemflow
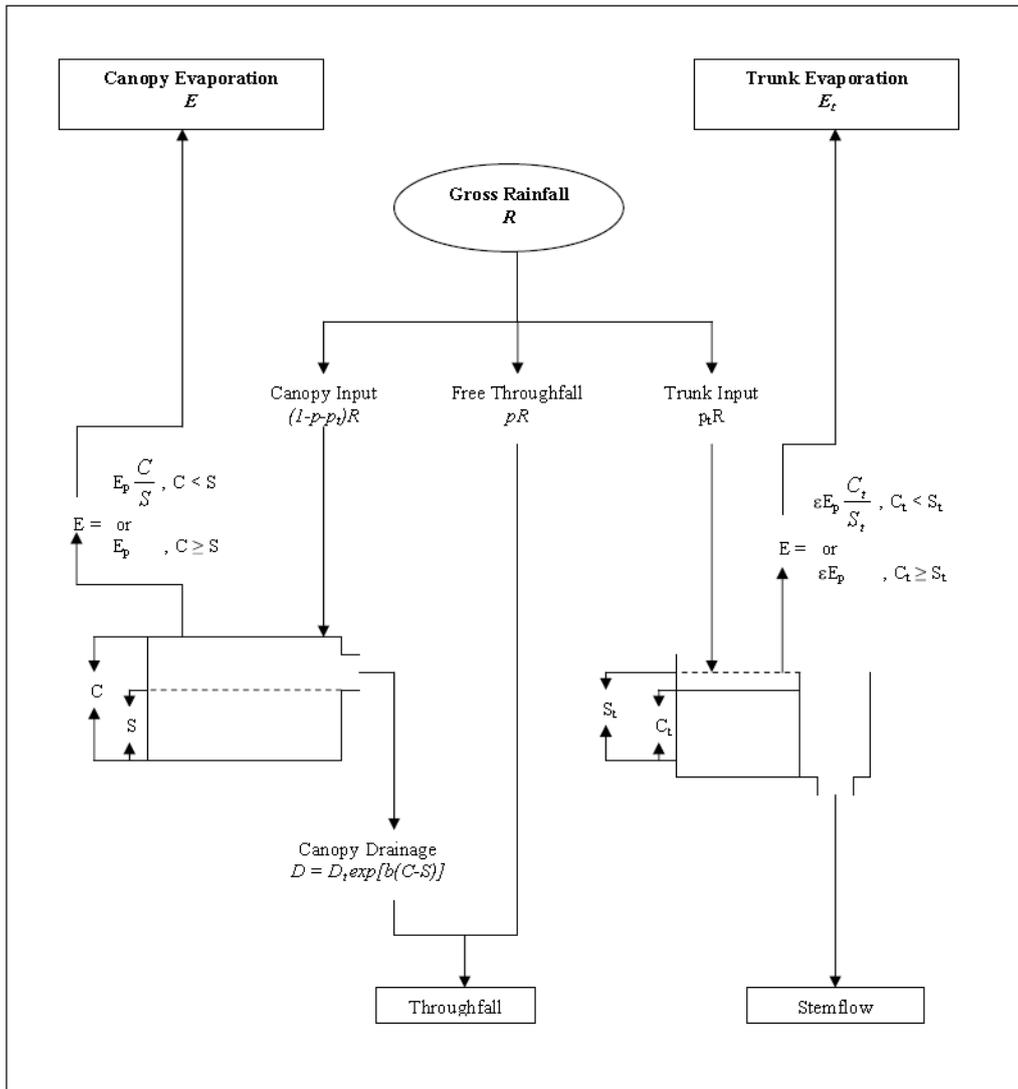
Figure 1.8   The conceptual framework of the Rutter model (After: Valente *et al*., 1997).

Later, Gash (1979) proposed a rainfall interception model, which is essentially a simplified analytical form of the Rutter *et al.,* (1971, 1975) model. While Gash (1979) recognised that Rutter's model was the most rigorous method for estimating interception loss at the time, he identified practical disadvantages in its use. Firstly, it requires detailed meteorological data and, secondly, it was computationally intensive. These two problems are however, not so significant today, as data collection and computational processing have advanced considerably (Llorens, 1997).

The Gash (1979) model is based on three main components;

1. the bulk rainfall input,
2. canopy structure parameters, and
3. evaporation of intercepted water.

The model is also based on three main assumptions, as follows;

1. the rainfall pattern is represented by a series of discrete storms which are separated by sufficiently long intervals to allow the canopy to dry,

2. the rainfall and evaporation rates are constant during the storm, and under conditions of canopy saturation the mean rainfall and evaporation rates are used, and

3. there is only one storm per rain day (which is a definite weakness of the model).

The original Gash (1979) model considers rainfall as a series of discrete events, during which three phases can be identified;

1. wetting phase,

2. saturation phase, and

3. drying phase after the rainfall has stopped.

The meteorological conditions prevailing during the first two phases are assumed to be the same and average values of gross rainfall intensity (R) and evaporation rate (E) for saturated canopy conditions are calculated for the whole simulation period and then applied in a generalised form to all individual rainfall events (Valente *et al*., 1997). The model uses total daily rainfall and assumes that there is only one storm per day and that there is sufficient time between storms for the canopy to dry (Zhang *et al*., 2006) in its calculation of canopy interception. The model was therefore not intended for use on short crops in temperate regions where the vegetation may stay wet for prolonged periods of time (van Dijk and Bruijnzeel, 2001a). Like the Rutter model, Gash's analytical model requires prior estimates of structural parameters of the forest canopy which are described in terms of the storage capacity (S), which is the amount of water left on a saturated canopy under conditions of zero evaporation after the rainfall and canopy drainage have ceased (Gash and Morton, 1978). The model also requires a free throughfall coefficient (p) and a stemflow coefficient (p_t). The Gash model has been used with considerable success to predict interception in a wide range of environments, including temperate coniferous and broadleaf forests, and tropical forests (van Dijk and Bruijnzeel, 2001a).

However, both the original Rutter *et al*., (1971, 1975) and Gash (1979) models only performed well for modelling interception in relatively closed canopies. This is especially true for the evaporative process, due to the assumption that the canopy and trunk storages extend to the whole plot area. Results from various studies (Lankreijer *et al*., 1993; Gash *et al*., 1995) suggest that the models should not be applied to sparse forests as the models tend to overestimate the interception loss. This led to the development of a 'sparse canopy' variant (Gash *et al*., 1995) in which evaporation from a wet canopy was considered linearly dependant on the canopy cover fraction (van Dijk and Bruijnzeel, 2001a).

Gash et al., (1995) revised the original model by addressing both a conceptual error and its poor performance in sparse canopy forests. This was corrected by introducing an additional parameter for the canopy cover fraction (c) as well as making the canopy storage (S_c) and the wet canopy evaporation rate linearly dependant on it. By doing this the conceptual error was removed, as it was assumed in the original model that the relative evaporation rate (E/R) was independent of ($1-p-p_t$). Had this not been corrected, a negative algorithm would result when calculating the rainfall necessary to saturate the canopy (P'_G), in a situation where ($1-p-p_t$)$R<E$ (Gash et al., 1995). Recent applications of the model indicate that it is suitable for predicting a wide range of conditions, from closed canopies to sparse canopies (David et al., 2005). The Gash models are the most extensively used interception model, having been reportedly used in 69 published papers, as of March 2008 (Muzylo et al., 2009).

Van Dijk and Bruijnzeel (2001a, 2001b) then modified the Gash et al., (1995) revised model by allowing it to be applied to rapidly growing vegetation where the leaf area index (LAI) is changing through time. The modifications are based on the following three
hypotheses:

1. The canopy capacity (S_c) is linearly related to LAI.
2. The relative evaporation rate (E/R) can be expressed as a function of LAI.
3. The water that is retained on the stems can be treated in a similar way to that retained by the canopy. (i.e. evaporation from saturated stems during the storm may be included in the simulations).

The modifications by van Dijk and Bruijnzeel (2001a, 2001b) to the Gash et al., (1995) model essentially revolve around the leaf area index parameter. For this model LAI is defined as the cumulative one-sided area of (healthy) leaves per unit area. LAI and the canopy cover fraction (c), can be related to one another via the Beer-Lambert equation that describes the attenuation of radiation (e.g. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate through leaves much, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between c and L is thus given by Equation 1.7

$$c = 1 - e^{-K.LAI} \qquad\qquad (1.7)$$

Where K is the extinction coefficient. The value of K for a particular radiation wavelength depends on the inclination angle and distribution of the leaves, and for PAR usually ranges between 0.6 and 0.8 in forests (van Dijk and Bruijnzeel, 2001a, 2001b).

The equations of the original Gash (1979) model, the revised Gash (1995) model for sparse canopies, and the adapted Gash model by van Dijk and Bruijnzeel (2001a, 2001b) are summarised in Table 1.2. The parameters are summarised and described in Table 1.3.

Table 1.2　　Equations used in the various versions of the Gash models (After: van Dijk and Bruijnzeel (2001a)

PARAMETER DESCRIPTION	ORIGINAL GASH (1979)	REVISED GASH *ET AL.*, (1995) FOR SPARSE CANOPIES	VAN DIJK AND BRUIJNZEEL (2001) VERSION OF GASH MODEL
Component of interception loss For *m* storms insufficient to saturate the canopy ($P_G \leq P'_G$)	$(1-p-p_t)\sum_{j-1}^{m}P_{Gj}$	$c\sum_{j=1}^{m}P_{Gj}$	$c\sum_{j=1}^{m}P_{Gj}$
For n storms sufficient to saturate the canopy ($P_G > P'_G$) Wetting up of canopy Wet canopy evaporation during storm . Evaporation after rainfall ceases	n{(1-p-p_t)P'_G-S} $\dfrac{E}{R}\sum_{j=1}^{n}(P_{Gj}-P'_G)$ nS	n{cP'_G-S} $\dfrac{E}{R}\sum_{j=1}^{n}P_{Gj}-P'_G$ Ns	$\sum_{j=1}^{n}c_j P_{Gj}-S_{vj}$ $\sum_{j=1}^{n}\dfrac{E}{R}(P_{Gj}-P'_{Gj})$ $\sum_{j=1}^{n}S_{vj}$
Evaporation from stems for q storms > St/pt, which saturate the stem and in the left column for the n + m - q, or in the middle column for the for the n - q, which do not.	$qS_t + p_t\sum_{j=1}^{m+n-q}P_{Gj}$	$qSt + pt\sum_{j=1}^{n-q}P_{Gj}$	Included in all above terms as the fraction $S_{s,j}/S_{v,j}$ of total interception loss
Rainfall necessary to saturate canopy	$P'_G = -\dfrac{RS}{E}\ln[1-\dfrac{E}{(1-p-p_t)R}]$	$P'_G = -\dfrac{RS}{E}\ln[1-\dfrac{E}{cR}]$	$P'_G = -\dfrac{RS_{vj}}{E_j}\ln[1-\dfrac{E_j}{c_j R}]$
Mean wet canopy evaporation rate	E = E_w	E = cE_c	$E_j = (1-e^{\alpha Lj})E_a$
Canopy capacity	S_c	S = cS_c	$S_{vj} = L_j S_L + S_{sj}$
Canopy cover fraction	1-p	c	$c_j = 1 - e^{-kLj}$

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Table 1.3   Summary of parameters used in the various versions of the Gash Model

Parameter	Description	Unit
P_g	Gross precipitation	mm.day^{-1}
E	Evaporation	mm.day^{-1}
R	Rainfall rate	mm.day^{-1}
p	Throughfall coefficient	-
p_t	Stemflow coefficient	-
S_c	Canopy storage capacity	mm
S_t	Trunk storage capacity	mm
c	Canopy cover fraction	-
P'_g	Rain to fill canopy	mm

More simple interception loss models such as the Von Hoyningen-Huene (1983) (Equation 1.8) which relates interception loss (mm.day^{-1}) to gross precipitation and LAI have also been used in hydrological models, such as the *ACRU* agrohydrological model (Schulze, 1995). Von Hoyningen-Huene (1983) in Schulze (1995) conducted extensive research on a number of agricultural crops and related their interception loss (mm.day^{-1}) to gross rainfall, P_g, and LAI as:

$$I_l = 0.30 + 0.27P_g + 0.13\text{LAI} - 0.013P_g.\text{LAI} - 0.007\text{LAI}^2. \tag{1.8}$$

However, it has been found that the equation is "stable" only for gross daily rainfall amounts that do not exceed 18 mm. Although the equation was developed for agricultural crops, Schulze (1995) found that the equation performed well on *Pinus patula*, and therefore it was deduced that the Von Hoyningen-Huene approach has potentially widespread application and is encouraged as the interception loss estimator in the ACRU agrohydrological model (Schulze, 1995).

5.   LITTER INTERCEPTION

Most forest stands have a forest floor of accumulated debris that the rainfall has to pass through before reaching the mineral soil (Jewitt, 2005). Although rainfall interception and transpiration by the canopy is responsible for most of the transfer of water and energy, a smaller, although significant role is played by forest floor evaporation. However, in some cases half or more of the total forest evapotranspiration originates from the forest floor evaporation process (Schaap and Bouten, 1997). Forest floor interception is the part of the net precipitation that is temporarily stored in the top layer of the forest floor and successively evaporated within a few hours or days, during and after the rainfall event (Gerrits *et al*., 2007). Litter may play an important role in increasing the infiltration rates in forest soils as well as protecting the soil from temperature and moisture extremes. The litter also provides protection to the soil surface from erosional forces such as raindrop impact (Jewitt, 2005). Litter interception is a function of litter mass per unit area, its water holding characteristics and its wetting frequency and rate of drying. Putuhena and Cordery (1996) demonstrated that the forest floor can retain a significant amount of water (1-3 mm), therefore affecting the flow into the soil and the water supply to vegetation. Because the litter on the forest floor is a very porous medium, the water is more easily evaporated than from the bare soil surface (Schaap *et al*., 1997). The litter layer has a significant effect on limiting soil water loss by evaporation and reducing the diurnal amplitude of soil temperature by reducing the night time heat loss and shading the soil during the day (Park *et al*., 1998).

The thickness and composition of litter varies during the season and from one location to the other, due to the characteristic cycling of litterfall and decomposition. Due to the spatial and temporal variability of the litter layer, evaluating the effect that the litter layer itself has on water vapour and heat transfer is difficult, leading to the scarcity of field studies about their fluxes (Park *et al*., 1998).

There have been very few studies on the storage capacity of forest floor litter (Putuhena and Cordery, 1996), but some researchers have tried to quantify the interception amounts. Helvey and Patric (1965) divided the methods of determining the interception amounts into two categories:

1. Laboratory methods, whereby field samples are taken and air dried in the labaratory. A drying curve for naturally drying litter samples is determined from calculations of moisture content in the litter in the days following a saturating rainfall event. A wetting curve is also required due to the fact that litter does not always dry out completely between events, or showers may be too light to saturate the litter. The moisture content of the litter is determined by mass and is compared to a dry mass for the sample which is obtained by oven drying the litter sample at $100^{o}C$ for 24 hours. The drying and wetting curves are then used as a basis for determining

litter interception loss. If the throughfall amount is known, the expected moisture content of the litter can be determined. It can therefore be said that litter interception loss is the difference between the measured and expected water contents (Jewitt, 1991).

2. Field methods, whereby litter is placed into trays or whereby sheets are placed underneath the forest floor and that permit throughfall in excess of litter interception to drain into the lower container. With the throughfall amount known, the litterflow amount can be determined, and the interception loss can be calculated.

According to Gerrits *et al.*, (2007) interception measurement studies have generally concentrated on canopy interception, but interception by the understorey and forest floor can be as high or even higher. The presence of litter modifies water and energy exchange between the soil and the air. As soil moisture and temperature are two major factors influencing soil respiration, these modifications have an important impact on the ecosystem carbon cycle (Ogée and Brunet, 2002). The forest floor is a source of heat, water vapour and CO_2 and its temperature and moisture regulate the rate of evaporation from the litter, as well as the rate of decomposition. The structural properties of a forest floor are highly variable both horizontally and vertically, but it is possible to consider the litter as a whole for a homogeneous vegetation cover (Ogée and Brunet, 2002). However, to understand the structural properties of the forest floor, a classification of the litter layers is required.

5.1 Forest Litter Classification

Most forests have a developed litter layer on the soil by an accumulation of leaves, twigs, bark and so on (Park *et al.*, 1998). The litter layer has an impact on the infiltration and runoff response of the forested catchment. The type of litter layer also influences these responses. Four layers have been identified by Hoover and Lunt (1952) to classify forest floor litter as shown in Figure 1.9. These are as follows:

- L layer - The first is the **L**itter layer or surface layer which consists of freshly fallen leaves, needles, twigs, stems, bark and fruits. In areas of high temperatures and rainfall here decomposition and incorporation are rapid, this layer may be thin or absent during the growing season. This layer is also referred to as the A_{o0} horizon.

- F layer - The **F**ermentation layer consists of partially decomposed material that is still recognisable to the original. This layer is also referred to as the A_{o1} horizon.

- H layer -   The **H**umus layer is that material that is well decomposed and is no longer recognisable as to the original. This layer is also referred to as the A_{o2} horizon.

- A_1 layer -   This is the surface mineral-soil horizon where organic matter is incorporated or infiltrated.
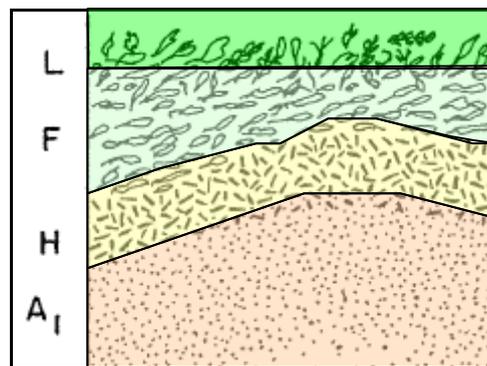
Figure 1.9   Forest litter layer classification according to Hoover and Lunt (1952).

The different litter layers have different water holding capacities and hence different hydrological impacts. Bernard (1963) cited in Jewitt (1991) found that the H layer and top few mm of the A_1 horizon are capable of holding up to 900% as much water as the L and F layers, despite having a dry mass of only 150% of these layers. From a hydrological point of view, it would appear that the H-layer of the forest litter plays a particularly important role in forest hydrology, as this layer has the potential to hold water like a sponge and gradually release water into the A_1 horizon, allowing almost total infiltration of throughfall for some events (Lowdermilk, 1930 cited in Jewitt, 1991).

To determine the interception capacity of the canopy vegetation, conventional rain gauges and trough gauges can be placed under the canopy. In a forested catchment where forest floor litter has developed on the soil surface, the surface litter will intercept both throughfall and stemflow. Miller (1977) in Putuhena and Cordery (1996) reported that typically, 1-3 $kg.m^{-2}$ of liquid water can be stored on forest vegetation, and a similar amount can be retained on the forest floor. The hydraulic mechanisms of the forest floor interception are similar to the canopy interception process.

Forest floor interception can be considered as a function of:
1. The accumulated mass of litter per unit area
2. The water retention characteristics of the litter (i.e. storage capacity)
3. The wetting frequency of the litter, and
4. The drying rate of the litter.

Thus the amount of rainfall intercepted is also similarly related to the water storage capacities of the surface components (Putuhena and Cordery, 1996). For forest floor litter however there are some obvious mechanical and spatial difficulties when measuring litter interception. The mechanical difficulty is due to the lack of space between the litter and the mineral soil or the grading of litter (H-layer) into the soil (A_1-Layer) (Putuhena and Cordery, 1996; Hoover and Lunt, 1952). In a catchment, the thickness of the litter layer can vary from a few millimetres to a few centimetres. The type and composition of the litter on the forest floor can also vary within the forest. The spatial variability of the amount and composition of the litter layer makes it difficult to measure the forest floor interception for a whole catchment. It is partly due to these inherent difficulties in making measurements of forest floor interception that there is a scarcity of information (Putuhena and Cordery, 1996).

6.   FOREST FLOOR EVAPORATION MODELS

Forest floor water content dynamics is a little studied subject in forest hydrological research. The importance of this research lies in the control the forest floor has over the transfer of water and energy between the sub-canopy atmosphere and the mineral soil (Schaap *et al.*, 1997). The forest floor is a source of heat, water vapour and CO_2 and its temperature and moisture regulate the evaporation from the litter (Schaap and Bouten, 1997). The litter moisture volume and litter (fuel) load are key factors for forest management as forest fires propagate more easily over dry forest floors (Ogée and Brunet, 2002). It is therefore useful to account for the litter moisture in soil-vegetation-atmosphere transfer (SVAT) models (Ogée and Brunet, 2002).

6.1   Forest Floor Water Dynamics

In a study by Schaap *et al.*, (1997) using the SWIF model (Soil Water In Forests), it was found that forest floor water content dynamics exhibit a similar behaviour to that of the underlying mineral soil. The litter layer is therefore considered as an integral part of the soil with a unique water retention curve and conductivity characteristic. The water content dynamics between the soil and the forest floor litter layer can be simulated using the Equation 1.9 (Richards, 1931).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\left(\frac{\partial h}{\partial z}+1\right)\right) - R(h) \tag{1.9}$$

Where, θ is the water content ($cm^3.cm^{-3}$), t is the time (day), z is the height (m), $K(h)$ is the hydraulic conductivity ($m.day^{-1}$), h is the pressure head (m), and $R(h)$ is the root water uptake function that is dependant on the pressure head.

In order to apply the Richards (1931) equation, water retention curves, conductivity characteristics, and boundary conditions need to be specified. The water retention and conductivity characteristics are described with the van Genuchten (1980) curves as expressed by Equations 1.10 and 1.11:

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{1+(\alpha|h|)^n)^m} \tag{1.10}$$

$$K(h) = K_s \frac{\left(1 - (\alpha|h|)^{n-1}(1 + (\alpha|h|)^n)^{-m}\right)^2}{(1 + (\alpha|h|)^n)^{m/2}}$$ (1.11)

Where, θ_r is the residual water content, θ_s is the saturated water content, α is the curve shape parameter (cm^{-1}), and n and m are also curve shape parameters.

Park *et al*., (1998) also used van Genuchten's (1980) closed-form equation to describe the soil water characteristic curves in the LITEM model, which is a numerical model used to evaluate the heat and water flows in a soil-litter-atmosphere system. The LITEM model is characterised by two features: firstly, simulation of the vapour and heat flow in the unsaturated litter layer and secondly, is to specify the surface boundary conditions in the model itself. An assumption of the LITEM model is the absence of plant water uptake (Park *et al*., 1998). The SWIF model used by Schaap *et al*, (1997) does however take plant water use into account as follows:

The potential plant transpiration (E_{pl}) is calculated from the potential evaporation and interception according to:

$$E_{pl} = f_c E_p - f_i I$$ (1.12)

Where, f_c is the crop coefficient that incorporates LAI dynamics, f_i is the interception efficiency, E_p is the potential evaporation, and I is interception loss.

The E_p is calculated using Makkink evaporation (Eq. 1.13) as it is easier to apply than the Penman-Monteith equation. However, the Makkink equation should only be used in the Netherlands.

$$E_p = (1 - f_g) \frac{0.65}{\lambda} \frac{s}{s + \gamma} Q \downarrow$$ (1.13)

Where, f_g is the gap fraction of the vegetation, λ is the latent heat of vaporization of water (J.kg^{-1}), s is the slope of saturated vapour pressure curve (Pa.K^{-1}), γ is the psychrometric constant (Pa.K^{-1}), and $Q\downarrow$ is the Global radiation (J.m^{-2}.day^{-1}).

For the root water uptake function *R(h)* in the Richards equation, the potential transpiration is distributed over the soil layers (*i*) using the 'effective' rooting length ($L_{ef,i}$) (Eq. 1.14), which is calculated as a product of the root length and a ratio of actual and saturated water content.

$$L_{ef,i} = L_i \times \frac{\theta_i}{\theta_{s,i}} \qquad (1.14)$$

The root uptake from layer i is calculated using the total effective root length, $L_{ef,tot}$ (m.m^{-3}), according to:

$$R_i(h) = E_{pl} \times RED(h) \times \frac{L_{ef,i}}{L_{ef,tot}} \qquad (1.15)$$

The total root water uptake (transpiration), E_{tr} (m.day^{-1}), is calculated over the N soil layers as:

$$E_{tr} = \sum_{i=1}^{N} R_i(h) \qquad (1.16)$$

RED(h) is a dimensionless reduction function that reduces the root water uptake in unfavourable wet or dry conditions. They are defined as follows:

$$RED(h) = 0 \text{ for } h > h_s \text{ or } h < h_w \qquad (1.17a)$$

$$RED(h) = \frac{(h - h_s)}{(h_l - h_s)} \text{ for } h_s > h > h_l \qquad (1.17b)$$

$$RED(h) = 1 \text{ for } h_l > h > h_r \qquad (1.17c)$$

$$RED(h) = 1 - \frac{(h - h_r)}{(h_w - h_r)} \text{ for } h_r > h > h_w \qquad (1.17d)$$

- Optimal root water uptake is between h_l (-2 cm) and h_r (-490 cm).
- Between h_r (-490 cm) and the wilting point, h_w (-10 000 cm), the root water uptake reduces to zero.
- Reduction occurs near saturation where the oxygen content in the soil limits root activity, (between h_s and h_l).
- At pressure heads greater than h_s (-1 cm) root water uptake is zero.

Once the movement of water between the soil and litter has been calculated, the movement of water from the litter to the atmosphere needs to be considered. The forest floor evaporation is calculated using the Penman-Monteith equation. Schaap *et al.*, (1997) used a conversion factor of 86.4 to convert the evaporation from kg.m^{-2}.s^{-1}, to m.day^{-1}.

The energy balance of the forest floor, illustrated in Figure 1.10, considering all upward fluxes and increases in heat storage as positive, can be written as (Equation 1.18):

$$A = -R_n + G - S_{ff} = \lambda E + H \qquad (1.18)$$

Where, A is the available energy (W.m^{-2}), R_n is the net radiation (W.m^{-2}), G represents the soil heat flux (W.m^{-2}), S_{ff} is the forest floor heat storage (W.m^{-2}), λE is the latent heat flux (W.m^{-2}), and H is the sensible heat flux (W.m^{-2}). If evaporation took place from the forest floor surface, the available energy is expressed as the sum of R_n and G (Schaap and Bouten, 1997).
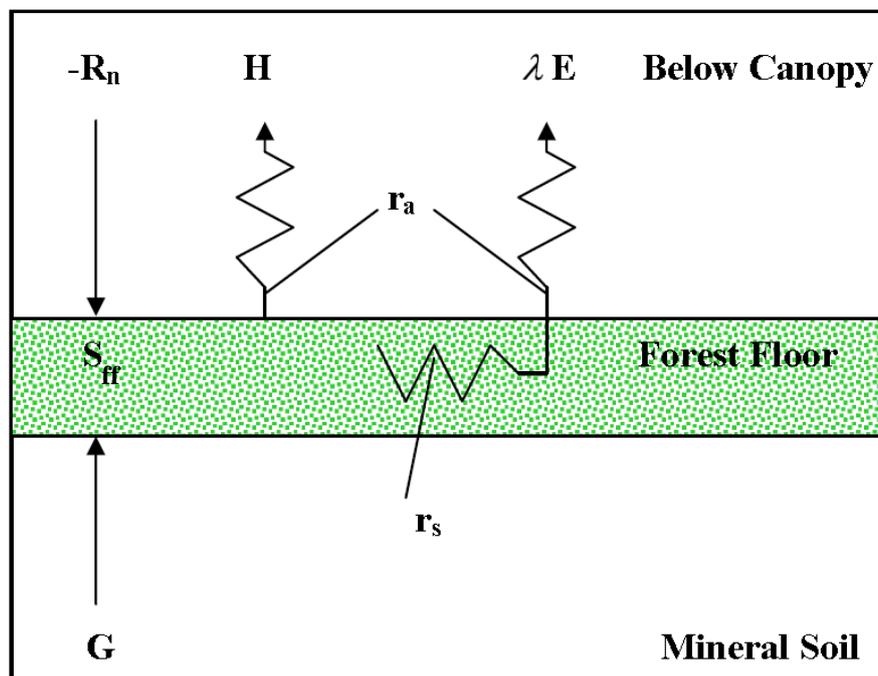
Figure 1.10   Schematic diagram of the forest floor energy balance (After: Schaap and Bouten, 1997).

However, in a study by Kelliher et al, (1986) in Schaap and Bouten (1997), it was found that forest floor evaporation may take place from within the forest floor as opposed to the surface. As evaporation requires energy, the forest floor heat dynamics (S_{ff}) needs to be included in the available energy term. In order to maintain the forest floor energy balance, the soil heat flux would need to be measured at the soil-forest floor interface, rather than the forest floor-atmosphere interface.

From a hydrological perspective, a litter model that can relate the litter moisture content to the litter type, mass and thickness while utilising easily measured climatic parameters such as rainfall, temperature and windspeed, would be beneficial as this would allow the hydrologist to estimate the amount of water that is held in the litter (intercepted) and is prevented from entering the soil (Jewitt,

1991). The forest litter also plays an important role in the forest water balance and related water fluxes due to the high proportion of fine roots in this zone. The amount of litter and fine root content on the forest floor vary considerably, depending on the soil nutrient status, which results in the water dynamics, including the root water uptake and drainage to the mineral soil also being highly variable. Apart from the ecological importance of the forest floor, in particular for the supply of water and nutrients to plants, there has been little progress in the study of its water dynamics. In most forest hydrological studies, the forest floor is neglected or treated as part of the mineral soil for which van Genuchten parameters have been estimated (Tobin Marin *et al*., 2000). It would therefore be particularly beneficial in the hydrological modelling of the forest water balance routines if the estimation of litter interception and its water dynamics were better understood, and it is this that will form a major part of this study.

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CHAPTER 2

Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands

Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands

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ABSTRACT

It is well accepted that the total evaporation in forested areas is greater than in grasslands, largely due to the differences in the amount of rainfall that is intercepted by the forest canopy and litter and higher transpiration rates. However, interception is the least studied of these components of the hydrological cycle. The study aims to measure and quantify the canopy and litter interception by *Eucalyptus grandis*, *Pinus patula* and *Acacia mearnsii*, at the Two Streams research catchment in the KwaZulu-Natal Midlands of South Africa for the three year period April 2008 to March 2011. The results from this study showed that canopy and litter interception contributed a significant amount of the water evaporated in a forest water balance. The canopy interception by *E. grandis*, *A. mearnsii* and *P. patula* was 14.9%, 27.7% and 21.4% of gross precipitation respectively, while litter interception was 8.5%, 6.6% and 12.1% respectively.

Keywords: Forest Hydrology, Canopy, Litter, Interception, Field measurements

1.   INTRODUCTION

It is well accepted that total evaporation in forested areas is larger than in grasslands, mainly due to the large amount of rainfall that is intercepted by the forest canopy (Bosch and Hewlett, 1982) and litter and higher transpiration rates. Although rainfall interception and transpiration by the trees canopy are responsible for most of the transfer of water and energy, a smaller but significant role is played by the forest floor litter interception (Schaap and Bouten, 1997). In some cases, half or more of the forests total evaporation originates from these processes *viz*. canopy and litter interception (Schaap and Bouten, 1997). This fraction of water is not available to the soil and thus modifies the balance of water and energy at the Soil-Vegetation-Atmosphere (SVAT) interface (Cuartus *et al*., 2007). It can therefore be said that interception is a threshold process and the first partitioning point in the forest

hydrological cycle, as a certain amount of precipitation is required to saturate the canopy as well as the litter storage capacity deficit before successive processes can take place.

The amount of canopy interception depends on several climatic factors. Climatic factors play a vital role in determining the amount of water that is intercepted. In most areas of the world there are large variations in the features of rainfall within and between seasons. These climatic conditions are important both during and after the event (Llorens *et al*., 2007). Evaporation during the event may comprise a substantial portion of the total amount of water evaporated (Crockford and Richardson, 1990; 2000). Water stored in forest canopies has been found to evaporate at rates in excess of potential evaporation due to advection and low aerodynamic resistance of wet canopies (David *et al*., 2005). The amount, intensity and duration of rainfall also play a vital role in determining the amount of interception. High intensity rainfall of short duration yields lower interception values than low intensity events of long duration. Discontinuous events also aid in yielding higher interception values.

Vegetation characteristics also play a vital role in determining the amount of rainfall intercepted. The storage capacity of the vegetation depends on the shape, orientation, density (leaf area index) and hydrophobicity of the leaves and branches (David *et al*., 2005). In this study, broad-leaf, needle-leaf and compound-leaf canopies were studied. Therefore, different trees with the same LAI may have very different storage capacities, depending on their leaf/canopy characteristics. Another important factor is whether the vegetation is deciduous or evergreen, as deciduous tree lose their leaves during the winter. In commercial forests, the age, planting density and management practices, such as whether the stand is thinned or pruned will also affect the canopy interception.

Although interception and transpiration by the canopy is responsible for most of the transfer of water and energy, a smaller, although significant role is played by litter interception (Schaap and Bouten, 1997). Litter interception is a function of litter mass per unit area, thickness and composition, its water holding characteristics, wetting frequency, and rate of drying. The thickness and composition of the litter varies during the seasons and from one location to the other, due to different characteristic cycling of litterfall and decomposition (Park *et al*., 1998). In this study, the litter of the three genera all have very different characteristics.

The processes of canopy and litter interception are however often not considered as significant processes in the hydrological cycle (Gerrits *et al*., 2006) and therefore not often studied. In addition, the difficulties inherent in interception measurements (Llorens and Gallart, 2000) may add to the reluctance of some researchers to address the role of interception fully. In South Africa, few studies of interception in forested areas have been undertaken and those that do exist are limited in their scope and wider applicability. In a study by Dye and Versfeld (1992) on a ten year old *Pinus patula* stand it

was found that the canopy interception was 14.8%. Versfeld (1987) measured canopy interception losses of 10.8% for *Pinus radiata*. However, there have been studies that have found canopy interception in a *Pinus sylvestris* as high as 42.2% in Scotland (Gash *et al*., 1980). Dye (1992) found canopy interception by four year old *Eucalyptus grandis* to be as low as 6% of gross precipitation. Langford and O'Shaughnessy (1978) measured canopy interception losses of 23.3% in a stand of *Eucalyptus regnans* in Melbourne, Australia. The only canopy interception results for *Acacia mearnsii* in South Africa are by Everson *et al*., (2006), who suggest that it is greater than 20%, while Samraj *et al*., (1982) found canopy interception by *A. mearnsii* to be 25% in Nilgiris, India. There have been even fewer litter interception studies in South Africa. Jacobz (1987) found litter interception in fifteen year old *Pinus patula* and *Pinus radiata* to be 16% and 32% respectively. Jewitt (1991) measured litter interception in four and eight year old *Eucaluptus grandis* and four year old *Pinus patula*. The results were a loss of 5.7%, 9.0% and 10.1% respectively. These results were however obtained from just 18 events. There have been no documented litter interception studies for *Acacia mearnsii*.

In 2007, Forestry South Africa (Godsmark, 2008) estimated that approximately 1.1% of South Africa was under plantation forestry, an area of 1 351 402 ha, the majority of which is located in the higher-rainfall eastern and southern regions of the country. These plantations comprise 53.5% pine, 37.7% eucalyptus, 8.1% wattle and 0.7% "other". Given that commercial forestry is a licensed water user, and that users have to pay for this use, it is important that water use, including interception are accurately quantified. Thus, this study aimed to measure and quantify the canopy and litter interception for typical sites of the three most common commercial forestry genera in South Africa, *viz*., *Eucalytus, Pinus* and *Acacia*.

2. MATERIALS AND METHOD

2.1 Site Description

The study took place between April 2008 and the end of March 2011 on Mondi Forests Mistley-Canema estate (30.67^{o}S, 29.19^{o}E) which is situated in the Seven Oaks district, about 70km north east of Pietermaritzburg in the KwaZulu-Natal Midlands, South Africa as shown in Figure 2.1. The site is classified as "moist midlands mistbelt" according to the South African Bioresource Group (BRG) classification system (Camp, 1997) and "midlands mistbelt grassland" by Mucina and Rutherford (2006). The climate is humid, with an annual rainfall ranging from 800mm to 1280mm per annum, most of which falls during the summer months between October and March. The summer rainfall is characterised by some high intensity storms as well as many low intensity events. During the winter months there are occasional low intensity frontal systems during this otherwise dry and often windy period. Additional moisture is provided by heavy mists which are a common feature. The mean annual temperature is 17°C. Prior to afforestation, the natural vegetation of the area was *Themeda triandra* grassland (Camp, 1997; Mucina and Rutherford, 2006). Only a few relic patches of *Themeda triandra* grassland remain, as the high potential of the arable areas has meant that little value has been placed on the natural vegetation. Commercial afforestation has been practiced in the area for a long time and is the most widespread land use, with gum (*Eucalyptus*.), pine (*Pinus*) and wattle (*Acacia*) being the genera of choice. Sugarcane is also grown at sites where drainage of cold air is good, ensuring that no frost or only light frost occurs (Everson *et al*., 2006). Experiments were set up at three sites within the estate for each of the three commercial forestry species and compliment an existing long-term water balance experiment. The study sites are shown in Figure 2.1 and the co-ordinates and elevation of the study sites are shown in Table 2.1.

Table 2.1   Co-ordinates of the study sites on the Mistley-Canema estate

SITE DESCRIPTION	LATITUDE (S)	LONGITUDE (E)	ELEVATION (M.A.S.L)
E. grandis	29°12'19.4"	30°39'12.5"	1069
A. mearnsii	29°12'19.4"	30°39'02.1"	1095
P. patula	29°11'06.4"	30°39'16.4"	1065
Automatic Weather Station	29°11'47.8"	30°39'58.4"	1098
Above canopy AWS	29°12'19.4"	30°39'12.5"	1070
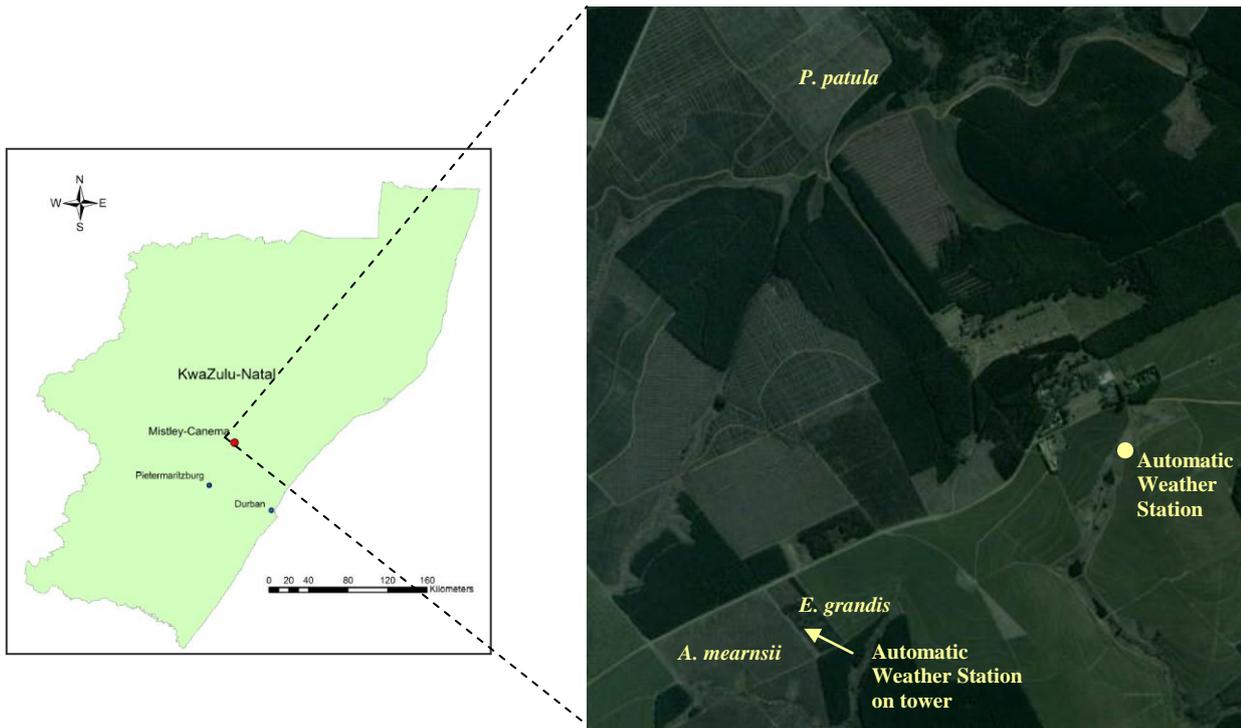
Figure 2.1   Location of Mistley-Canema Estate in KwaZulu-Natal, South Africa (Google Earth, 2009).

2.2   Forest Stand Description

In this study, canopy and litter interception for typical sites of the three most common commercial forestry genera in South Africa, *viz.*, *Eucalyptus, Acacia* and *Pinus* were measured. Eucalypts are usually planted at 1666 spha (stems per hectare) and clearfelled at 7 to 10 years of age. The *Eucalyptus* stand used in this this study was planted at 1600 spha and was 5 years of age. Pines are usually planted at a density of 1111 spha for sawtimber and up to 1736 spha for pulpwood. Pulpwood stands, such as the stand used in this study are usually felled between 15 and 18 years, while sawlogs have a longer rotation and are felled at between 20 and 30 years. As the Pine stand used in this study was planted for pulpwood, the planting density of 1600 spha is typical. *Acacica mearnsii* are primarily used for its high tannin content in the bark, but is also used for pulping. *Acacia mearnsii* are usually grown at a density of approximately 1500 spha and felled at between 8 and 12 years (Zwolinski and Bayley, 2001). The *Acacia mearnsii* stand used in this study was planted at a lower density than usual at 1111 spha. The characteristics of the forest stands are summarised in Table 2.2.

Table 2.2   Summary of forest stand characteristic for the study sites at Two Streams as of March 2011

Species and compartment number	Age (Yrs)	Height (m)	Mean Diameter at Breast Height (cm)	Planting density (spha)	Management Practice	Max LAI	Average Litter Thickness (mm)	Litter mass/unit area (kg.m^{-2})
E. grandis (T005A)	5	14.3	15.2	1600	Pruned	2.7	38	2.32
A. mearnsii (C005)	5	13.6	13.5	1111	Thinned and pruned	2.3	20	2.40
P. patula (B053)	16	16.1	28.4	1600	Thinned and pruned	1.9	97	3.34

2.3   Weather Data

Gross precipitation and reference evaporation data were supplied by the CSIR from two automatic weather stations forming part of the ongoing Water Research Commission (WRC) project. An energy balance weather station was situated between the *A. mearnsii* and *E. grandis* sites and was mounted on a tower above the canopy (Figure 2.2). A Campbell Scientific automatic weather station was programmed to measure American Society of Civil Engineers - Environmental and Water Resources Institute (ASCE-EWRI) reference evaporation and was situated approximately 1.7 km from the *P. patula* site in an open kikuyu grassland as shown in Figure 2.3. The automatic weather station measured solar irradiance (W.m^{-2}), ambient temperature (^{o}C), relative humidity (%), rainfall (0.1 mm), windspeed (m.s^{-1}) and direction (^{o}) at 10min, 20min and hourly intervals and calculated reference evaporation hourly and daily. The energy balance automatic weather station measured net irradiance (W.m^{-2}), air temperature (^{o}C), relative humidity (%), rainfall (0.1 mm), windspeed (m.s^{-1}) and direction (^{o}), soil temperature (^{o}C) at 20 mm and 60mm, and soil heat flux at 80 mm (W.m^{-2}) (Clulow, 2007).

Figure 2.2   Automatic weather station above *Acacia mearnsii* and *Eucalyptus grandis* canopies (Clulow, 2007).
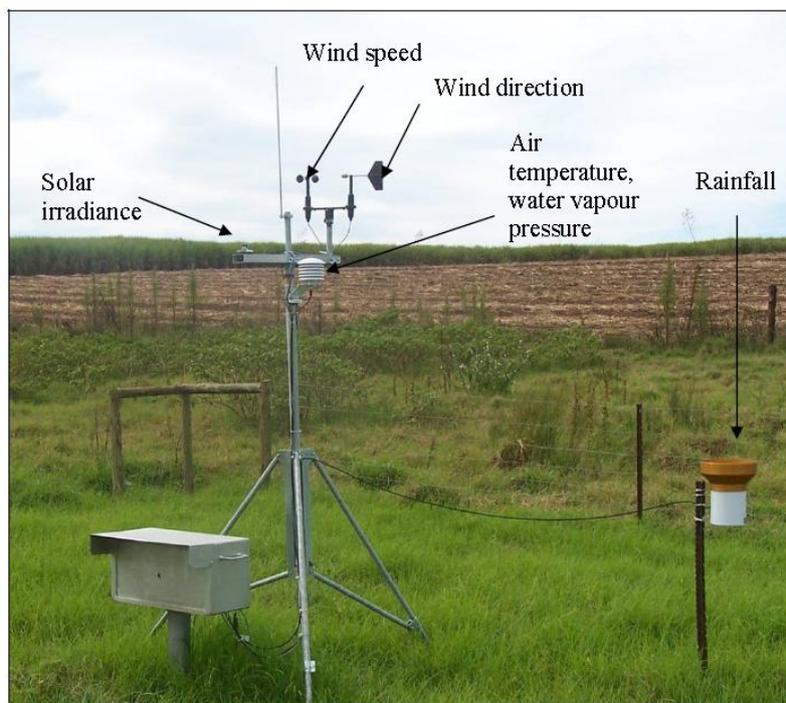
Figure 2.3   Automatic weather station used for *Pinus patula* gross precipitation (Clulow, 2007).

The historic rainfall record from September 1998 to March 2011, as well as the rainfall during the study period from April 2008 to March 2011 is illustrated in Figure 2.4. Both periods show a similar rainfall distribution, indicating that the study period was typical in terms of rainfall. The high percentage of "small" events is noticeable. Rainfall events less than 1 mm account for 50.8% of the events during the study period. The events below 4.0 mm account for approximately 73.6% of all the rainfall events during the study period. This is significant, because during these "small" events, it is likely that most of the rainfall will be intercepted by the canopy and the litter, depending on the antecedent canopy and litter moisture content.
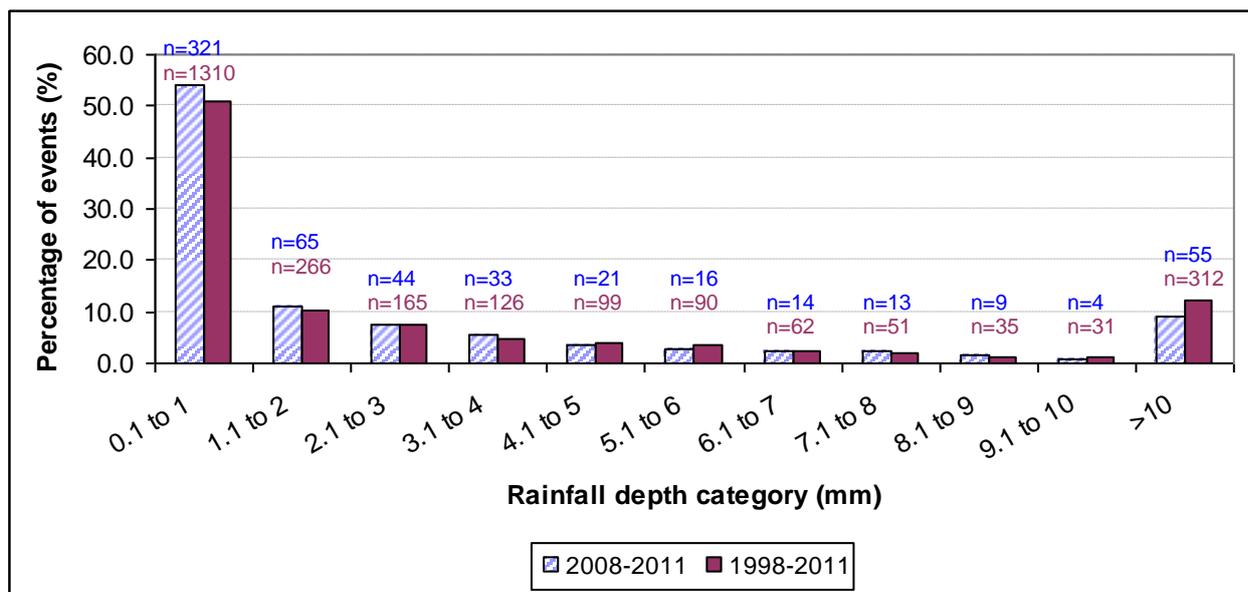
Figure 2.4   Percentage of rainfall events per rainfall depth category (n=595 and n=2577).

2.4   Canopy Interception Measurements

Throughfall measurements were made using a nest of three "V" shaped troughs at each site, constructed from galvanised iron sheeting (Figure 2.5) based on the design of Cuartus *et al.*, (2007). The dimensions of each trough were 0.1 m wide x 2.0 m long. Conventional "U" or "V" shaped troughs are susceptible to blockage by fallen debris and water loss from splash out, however, this system minimizes splash out by using steep "V" shaped sides. The troughs were covered with mosquito netting to minimize the entry of debris, which reduced the demand of cleaning and maintaining the system. A correction factor for each trough was derived from laboratory measurements to account for the "initial abstraction" from the netting. The three troughs were then connected to a single tipping bucket gauge and an event data logger. Because the trough represents a linear and continuous sampling surface, the linear variation of leaves, branches, and tree crown, its catches were assumed to be a representative integral of throughfall. A shortcoming of the throughfall troughs was that they were still susceptible to occasional blockages (8 out of 595 events i.e. 1.3%) during large rainfall events, particularly at the *A. mearnsii* site which has very small compound leaves

that were still able to fit through the netting. From field observations and analysis of the raw data, such events were patched for further analysis in this study. One nest of three troughs was decided to be sufficient, due to the uniform spacing of the trees in the plantation. Also, the radial arrangement of the three troughs accounts for the linear variability within the canopy. A similar sampling strategy was used by Cuartus *et al.*, (2007).

Figure 2.5(a)   Throughfall troughs with mosquito netting covering. (b) showing the blockage of a trough.

2.5   Leaf Area Index Measurements

The LI-COR LAI-2000 plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, Nebraska, USA) was used to measure plantation forests single sided LAI. Due to the height of the trees, it was not possible to take measurements above the canopy. Thus the "remote mode" method was used, i.e., two control units are used to log the above and below canopy readings simultaneously. Ten sets of four readings were taken for each plot, each point being taken at random points and orientations beneath the canopy. At the same time, a separate synchronised instrument was located in an open area and took readings every 15 seconds, representing the above canopy readings. Light readings made below the canopy are divided by readings made above the canopy to compute transmittances at five angles. A control unit records these readings and calculates LAI from the transmittances (Clulow, 2007). During the data processing stage the above and below canopy readings were compared to determine the fraction of light transmitted or absorbed by the canopy. A sunlit canopy was avoided by taking readings just before sunset when the solar elevation is low (below 45°). A 45° view restrictor was used to block the sensor in the field of view of the operator. This procedure was followed for all sites and values are shown in Table 2.2. One problem that was not accounted for is that the LI-COR LAI-2000 was shown by Gower and Norman (1990) to underestimate LAI in conifer stands by 35-40%. This is due to the fact that the instrument is sensing projected area of shoots, rather than needles. They found that a correction factor, which is based on the shoot morphology and can be independently measured, and appears to adequately compensate for this. Their suggested technique is to determine the ratio of projected shoot area to total needle area for the particular species being measured, and then multiply the results by this ratio.

2.6   Litter Interception and Water that Drains to Soil

The experiment layout for measuring litter interception and water that drains to the soil is shown in Figure 2.6a, b and c. The litter interception and water that drains to the soil were measured using two round galvanized iron basins that fit into each other. Two litter interception basins were placed in each site to account for the spatial variability of the litter thickness. The upper basin which had an inner diameter of 0.5 m was filled with litter and had a geotextile lining on top of a wire mesh base, so that water could percolate into the lower basin, but the fine particles from the litter are retained. A flat spade was used to slide under the litter at the litter-soil interface as carefully as possible so as to limit the disturbance of the sample. This sample was then places into the interception basin. The water that was collected in the lower basin drains into a Davis tipping bucket (Davis Instruments, 2001) and the water that would have drained to the soil was recorded with a HOBO$^®$ pendant event logger (Onset Computer Corporation, 2005).   The litter interception is then calculated as the difference between throughfall measurements obtained and the water that drained to the soil.   The experiment was replicated twice at each of the three sites.
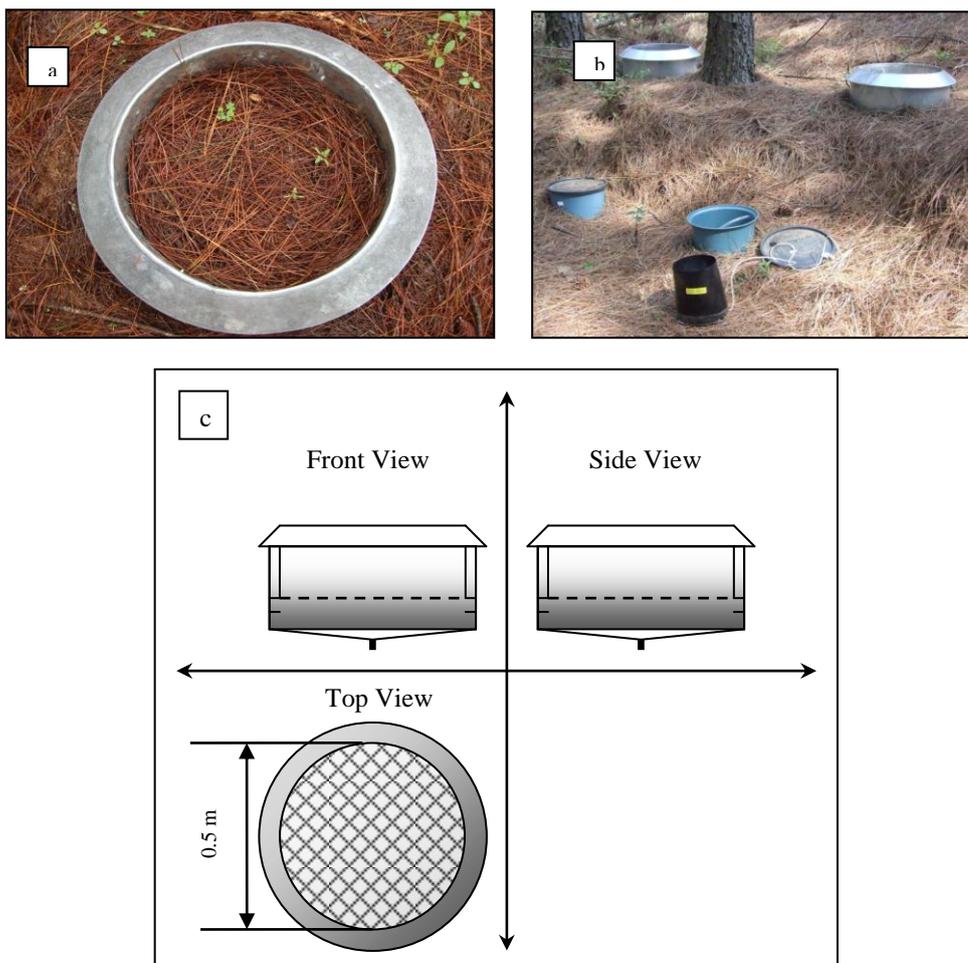
Figure 2.6(a)   Top view of litter interception equipment. (b) Litter interception equipment and tipping bucket raingauge that is housed in the blue buckets. (c) Schematic of litter interception equipment.

2.6.1　Possible errors in litter interception measurements

Litter interception is not well studied, and for good reason. One reason is that it is not easy to measure. There are a number of potential errors that may influence the litter interception results. Inherent in many field experimental setups is the disturbance of the system, leading to possible errors. One such error arises from transferring the litter from the forest floor to the interception basin, where the sample may not be compacted to the same density, thickness or composition as it was on the forest floor. Similarly, by removing the sample from the forest floor, the interaction between the forest floor soil and the litter is lost, and water that enters the litter ought not to be considered as an entirely separate store from soil water. This is highlighted by Schaap *et al.*, (1997) who modelled the forest floor litter moisture content dynamics as another "soil" layer, using a physically based model (*cf.* Chapter 1, Section 6). It is also often very difficult to define the boundary between the humus layer (H-layer) and the A_1-layer where the organic matter and mineral soil and incorporated (*cf.* Chapter 1, Section 5). Furthermore, fine roots in the litter from the trees or understorey vegetation are no longer able to access the water in the litter. Another potential error is introduced by the use of geotextile or any other artificial barrier. It has been noted by Helvey and Patric (1965) and Gerrits (2010) that the geotextile may cause water accumulation on the interface before drainage starts. A further error may be introduced due to the fact that the litter interception basins are positioned approximately 10 cm above the ground. This can alter the wind flow, causing turbulence and therefore potentially increasing the evaporation. In this study, the wind effect was minimised by having angled sides on the rim of the litter interception basins, making it more aerodynamic as can be seen in Figure 2.6. However, the windspeed under the canopy is very low, and therefore, the effect of wind under the canopy is significantly reduced. Gerrits (2010) used a similar system to the one used in this research, where one basin is suspended above another. However, the system used by Gerrits (2010) attempted to measure litter interception directly by using strain gauge sensors to measure the change in mass of the top basin. This change in mass could then be used to calculate the evaporation from the litter. This method did however also have many potential sources of error. The main source of error was due to the strain gauges being sensitive to temperature and thereby causing measurement errors. Gerrits (2010) attempted to correct this error by using a so called "dummy sensor" to compensate for the influence of temperature. In an environment with high temperatures such as in South Africa, it was decided that this system would not be used.

3. RESULTS

The observed results of this study are presented for the period April 2008 to March 2011, with canopy interception, canopy storage capacity, litter interception and the amount of water that drains to the soil for *E. grandis, A. mearnsii* and *P. patula* being the foci.

3.1 Canopy Interception and Storage Capacity

The relationship between gross precipitation and canopy interception for *E. grandis, A. mearnsii* and *P. patula* are illustrated in Figures 2.7, 2.8 and 2.9 from the field measurements for each event obtained at Two Streams from April 2008 to March 2011.
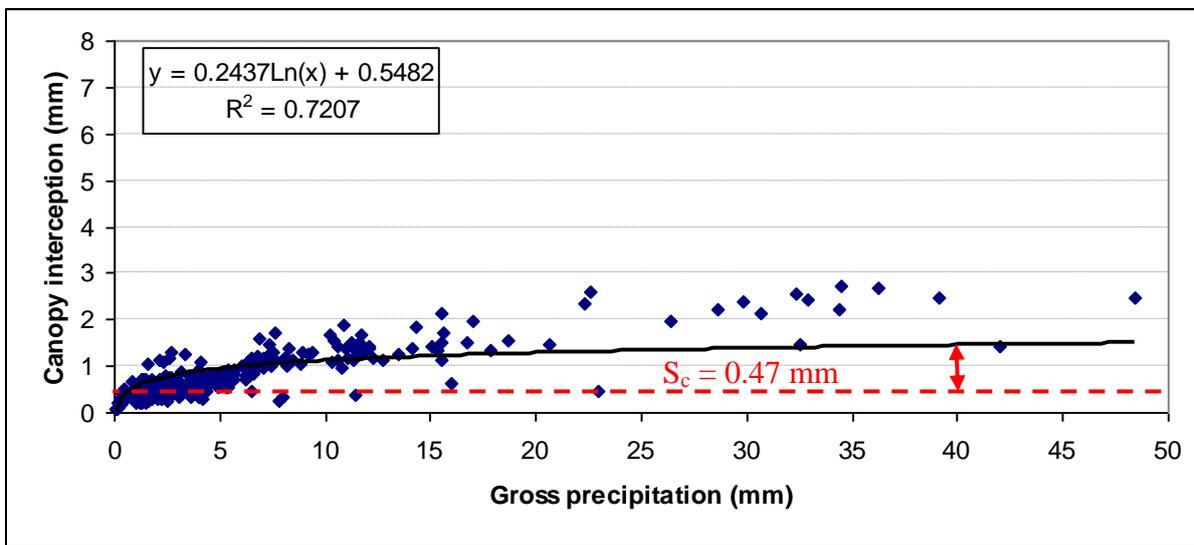
Figure 2.7   Canopy interception by *Eucalyptus grandis* (n=565) at Two Streams.
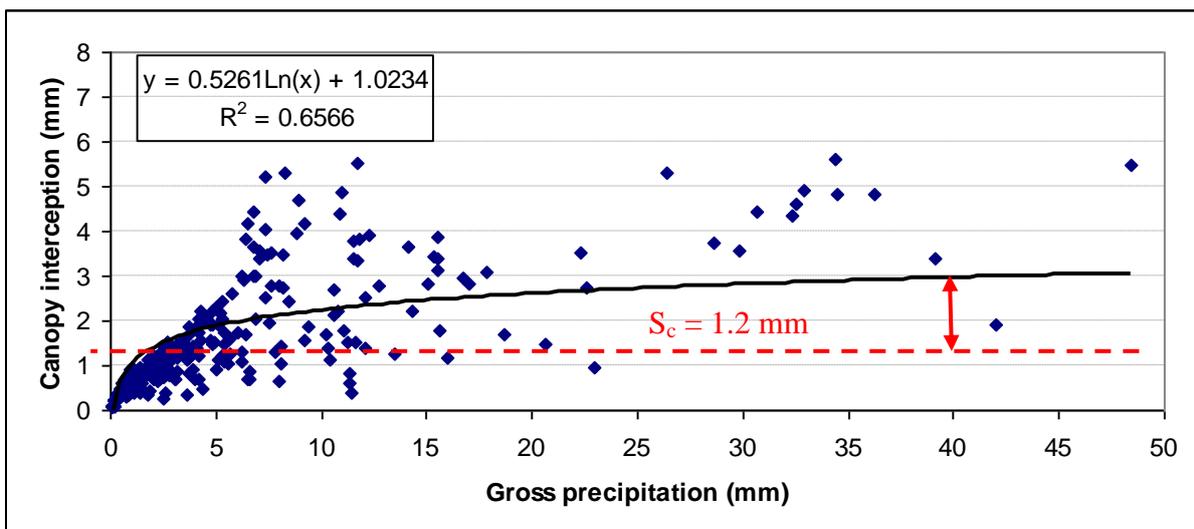
Figure 2.8   Canopy interception by *Acacia mearnsii* (n=565) at Two Streams.
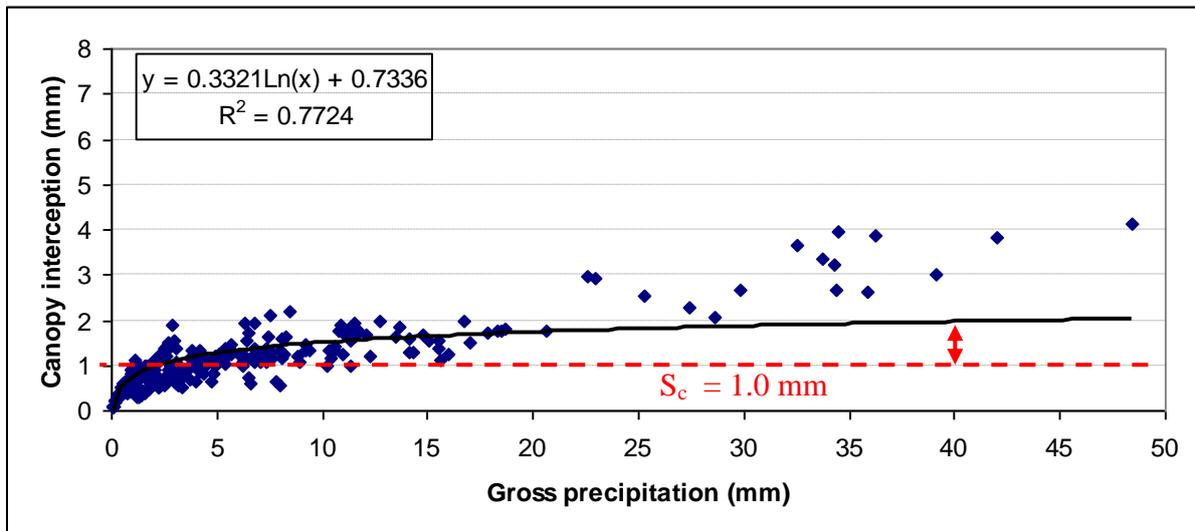
Figure 2.9   Canopy interception by *Pinus patula* (n=565) at Two Streams.

The logarithmic relationship between gross precipitation found in this study is consistent with other research undertaken in South Africa, such as that done by Schulze *et al*., (1978) on a *Pinus patula* stand at Cathedral Peak in KwaZulu-Natal. Although the log function may not fit the data very well, it does illustrate the fact that there is still wet canopy evaporation after the storage capacity of the canopy has been reached. This is illustrated by the arrow showing evaporation after the storage capacity has been reached. If there was no wet canopy evaporation, then interception would be equal to the storage capacity. The results of the total canopy interception during the study period for *E. grandis, A. mearnsii* and *P. patula* are presented in Table 2.3.

Table 2.3   Total observed canopy interception from April 2008 to March 2011.

Species	Gross Precipitation (mm)	Observed canopy interception (mm)	Observed canopy interception (%)
E. grandis	1884.7	280.4	14.9
A. mearnsii	1884.7	522.4	27.7
P. patula	1909.7	408.7	21.4

From Table 2.3 it can be seen that *A. mearnsii* has the highest canopy interception loss over the study period, followed by *P. patula* and *E. grandis* respectively. *Acacia mearnsii* intercepted 27.7% of the gross precipitation, and *P. patula* and *E. grandis* intercepted 21.4% and 14.9% respectively. The higher than expected canopy interception result can be partly attributed to the high percentage (61.2%) of rainfall events less than 2 mm where almost 100% of the precipitation is intercepted.

The relationships between gross precipitation and canopy interception as a percentage of gross precipitation is illustrated in Figures 2.10, 2.11 and 2.12. Canopy interception results are often

represented as a percentage of gross precipitation as a means to estimate the canopy storage capacity. The maximum amount of gross precipitation to be totally intercepted by the canopy is the canopy storage capacity as illustrated by the broken red line in Figures 2.10 to 2.12. The storage capacity was estimated by analysing the data for the highest rainfall event to result in complete (100%) interception. Despite many studies using this method, it is however a simplistic method of estimating canopy storage capacity and not necessarily accurate. Canopy storage capacity will be discussed in more detail later in this section.
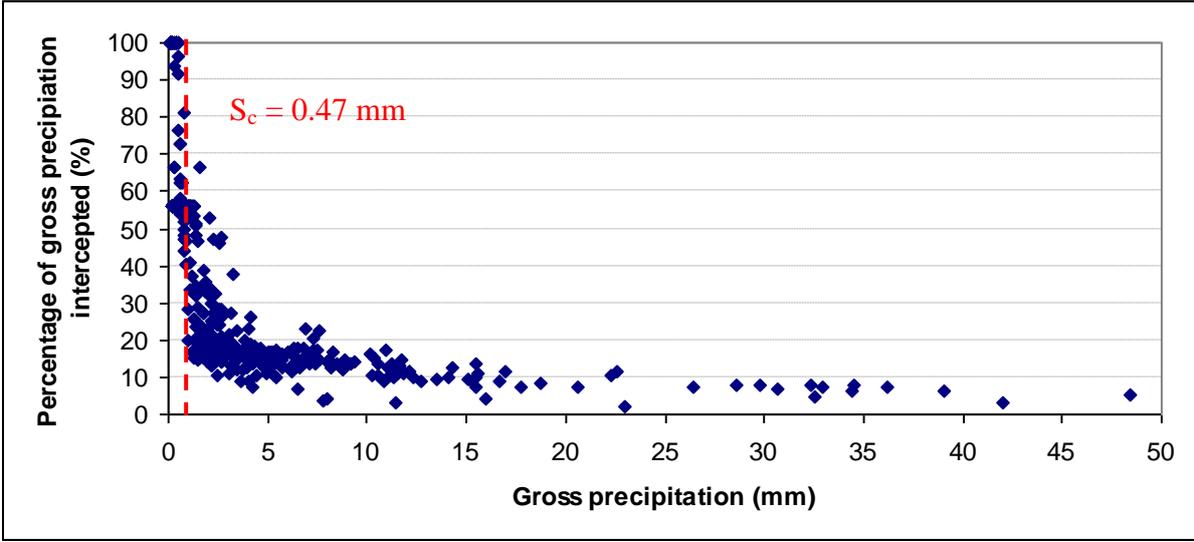
Figure 2.10   Percentage of gross precipitation intercepted by the canopy of *Eucalyptus grandis* (n=565). The canopy storage capacity (S_c) is indicated by the red line.
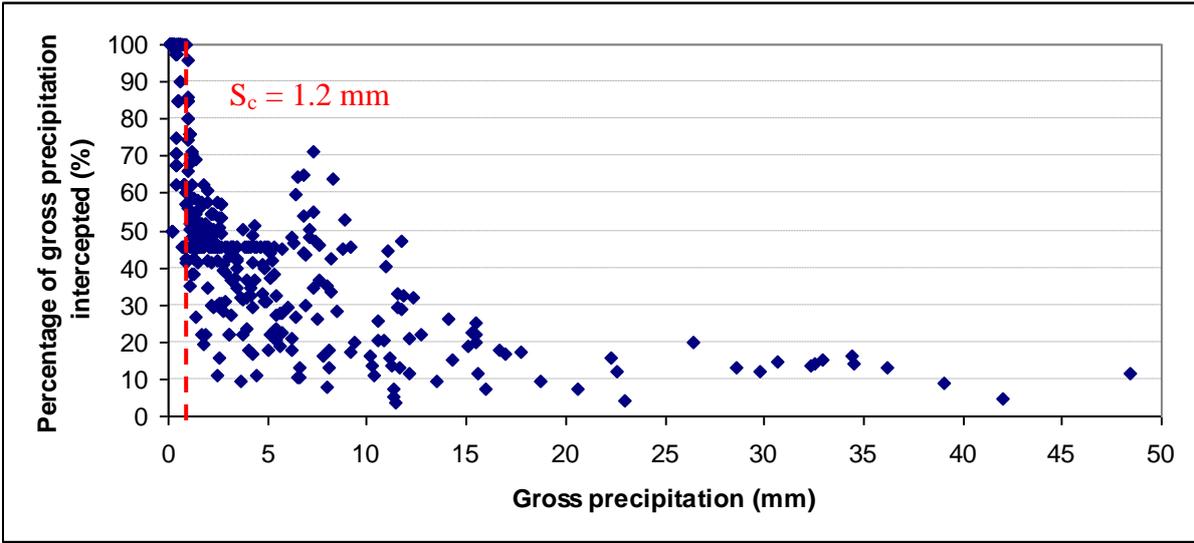
Figure 2.11   Percentage of gross precipitation intercepted by the canopy of *Acacia mearnsii* (n=565). The canopy storage capacity (S_c) is indicated by the red line.
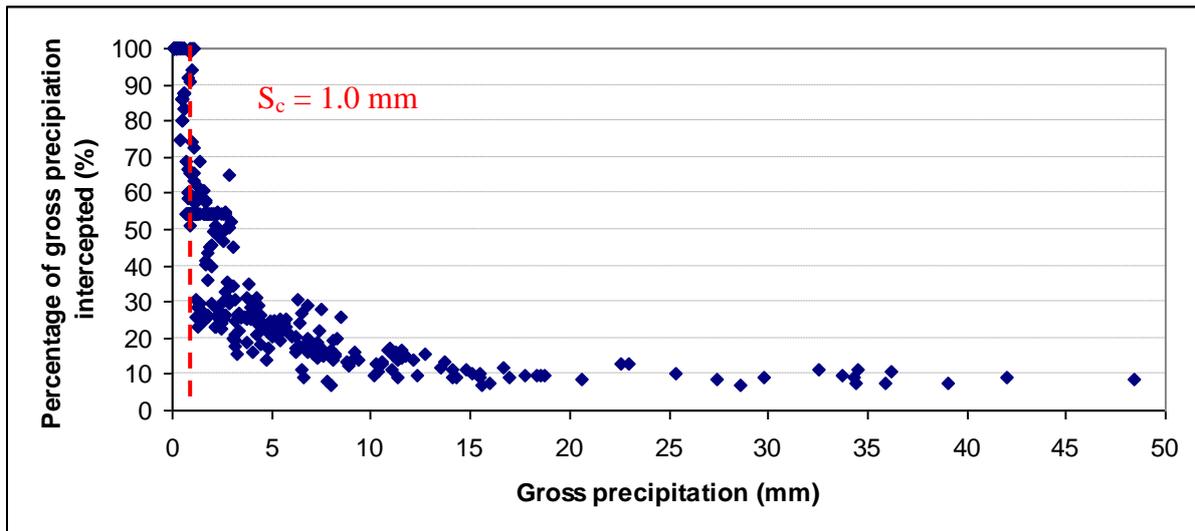
Figure 2.12   Percentage of gross precipitation intercepted by the canopy of *Pinus patula* (n=565). The canopy storage capacity (S_c) is indicated by the red line.

The canopy storage capacity for *E. grandis, A. mearnsii* and *P. patula* are illustrated by the broken red line in Figures 2.10 to 2.12 respectively. It was found that *E. grandis* had canopy storage capacity of 0.47 mm, which was the lowest of the three species investigated in this study, although it had the highest LAI of 2.7. The storage capacity for *A. mearnsii* was found to be 1.2 mm and *P. patula* was 1.0 mm. *Acacia mearnsii* and *P. patula* had LAI's of 2.3 and 1.9 respectively. The storage capacity is an important parameter to estimate when considering that interception is a threshold process, and only once the storage capacity has been reached does most of the throughfall and subsequent hydrological processes take place, although there is a small amount of direct throughfall before the storage capacity is reached. It can be seen in Figures 2.10 to 2.12 that there are a few events that are less than the storage where there is not 100% interception. This may be attributed to consecutive rainfall events taking place before the canopy has had sufficient time to dry out completely, thereby effectively decreasing the canopy storage capacity. The canopy storage capacity was also found to vary with the intensity of the rainfall event as shown in Figure 2.13.
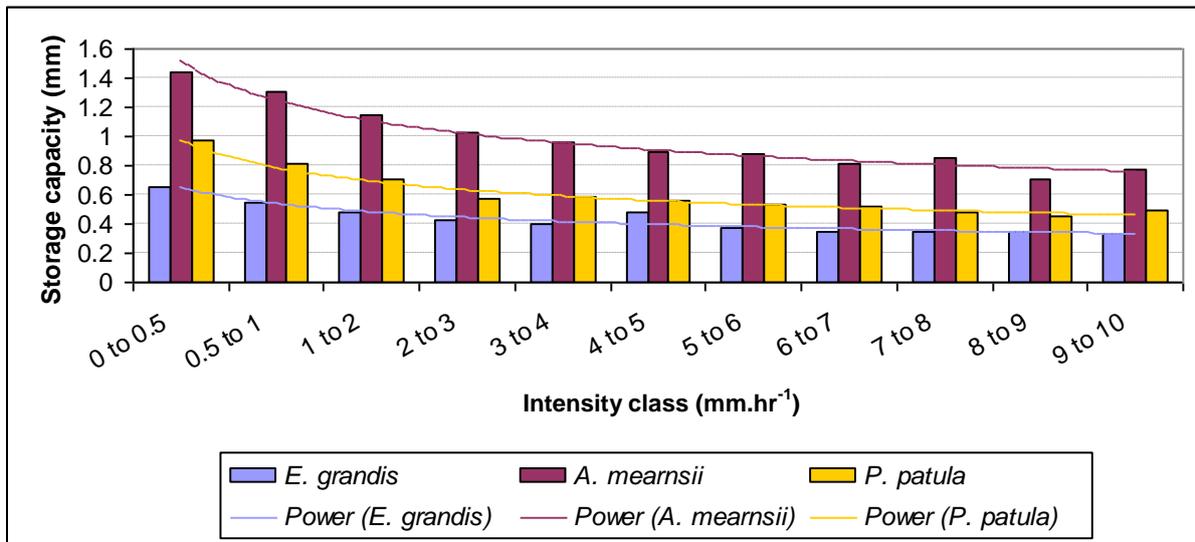
Figure 2.13   Canopy storage capacity for *E. grandis*, *A. mearnsii* and *P. patula* at different rainfall intensities.

By analysing the gross precipitation and throughfall data which was recorded at 10 minute and "per tip" time steps respectively, the rainfall intensity and storage capacity could be estimated accurately. This was done by isolating as short a period after saturation as possible so that wet canopy evaporation was minimised to estimate the canopy storage capacity by subtracting the throughfall from the gross precipitation. The rainfall intensity and storage capacity could therefore be calculated. As shown in Figure 2.13, it was found that low intensity events resulted in a higher canopy storage capacity than high intensity events. These results are corroborated by Calder, (1986) and Hall, (2003). Due to the lower kinetic energy of low intensity rainfall events, the raindrops are able to settle on the leaves and branches. Conversely, High intensity events are normally characterised by larger raindrops with greater kinetic energy as well as turbulent conditions which are able to "dislodge" the raindrops from the canopy, thereby not allowing as much precipitation to settle. This does not necessarily mean that the interception will be lower for high intensity events, as the wet canopy evaporation may be high during these events. What can also be seen in Figure 2.13 is that there was little change in storage capacity at rainfall intensities greater than 3 to 4 mm.hr^{-1} for *Pinus patula* and *Acacia mearnsii*, whereas the storage capacity does not change much after 1 to 2 mm.hr^{-1} for *Eucalyptus grandis*. These findings also highlight the importance of the water holding characteristics of the canopy due to leaf texture and leaf orientation. This is most evident by considering *E. grandis* which has the largest LAI, but the smallest canopy storage capacity due to its smooth, "waxy" leaves that repel water effectively, as well as the angle at which the leaves hang. The canopy storage capacity range and the trendline equations are shown in Table 2.4.

Table 2.4   Storage capacity ranges and trendline equations for *E. grandis*, *A. mearnsii* and *P. patula.*

Genus	Storage capacity range (mm)	Trendline Equations
E. grandis	0.33 - 0.65	$S_c = 1.525x^{-0.29}$
A. mearnsii	0.77 – 1.44	$S_c = 0.659x^{-0.28}$
P. patula	0.55 – 0.98	$S_c = 0.981x^{-0.32}$

The storage capacities and equations in Table 2.4 are site specific and therefore should not be extrapolated to other areas, as these values will change depending on the LAI.

To further emphasise the importance of fully understanding the role that rainfall amount, intensity, duration and frequency play in canopy interception, two contrasting periods of February 2009 and February 2010 are shown in Table 2.5.

Table 2.5   Observed canopy interception by *E. grandis*, *A. mearnsii* and *P. patula* for the two contrasting periods of February 2009 and 2010.

Time Period	Gross Precipitation (mm)	*E. grandis*		*A. mearnsii*		*P. patula*		No. of events
		(mm)	(%)	(mm)	(%)	(mm)	(%)	
Feb 2009	216.4	21.5	9.9	39.4	18.2	31.2	14.4	21
Feb 2010	43.0	9.1	21.2	13.5	31.4	11.1	25.8	17

As shown in Table 2.5, for the two contrasting time periods of February 2009 and 2010 where in February 2009 there was 216.4 mm of rainfall in comparison to February 2010 where there was almost five times less rainfall at 43.0 mm. Although there was a large difference in the rainfall during these two periods, there was not a large difference in the number of events. Due to the larger rainfall events of higher intensity in February 2009, the canopy interception expressed as a percentage of gross precipitation is far lower that in February 2010 which had fewer, low intensity events. The canopy interception in February 2009 was for *E. grandis, A. mearnsii* and *P. patula* was 9.9%, 18.2% and 14.4% respectively, in comparison 21.2%, 31.4% and 25.8% respectively.

3.2 Litter Interception

The results of the litter interception study are illustrated in Figures 2.13 to 2.16. Figures 2.17 to 2.19 illustrate the relative portions of gross precipitation that are lost due to canopy and litter interception. The remaining water that is not intercepted and drains to the soil is summarised in Table 2.4.
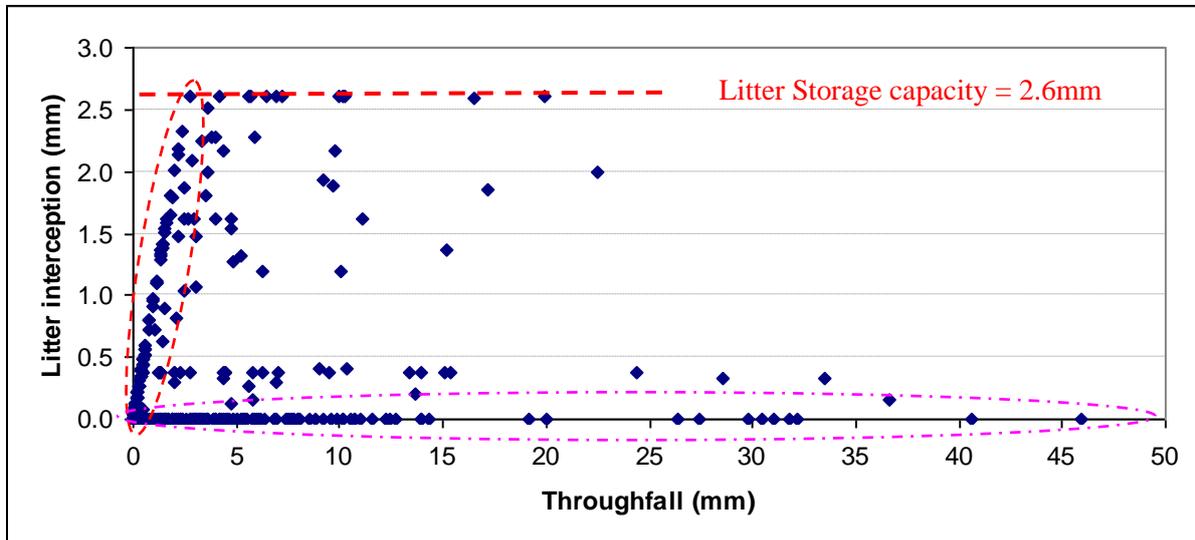
Figure 2.14   Observed litter interception by *Eucalyptus grandis* at Two Streams. The red circle represents increasing litter interception with increasing throughfall.
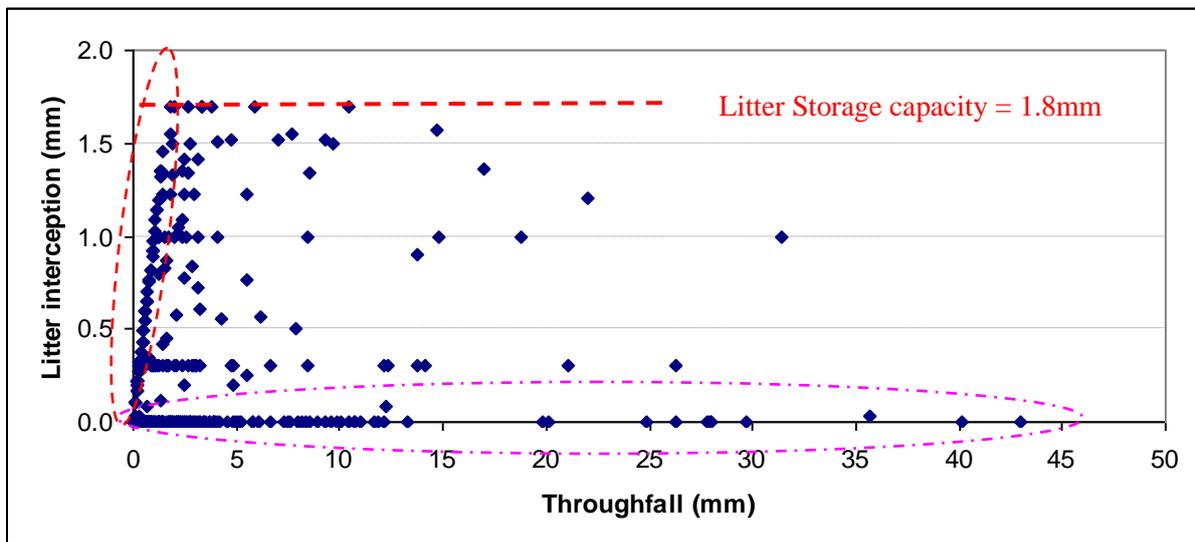
Figure 2.15   Observed litter interception by *Acacia mearnsii* at Two Streams. The red circle represents increasing litter interception with increasing throughfall.
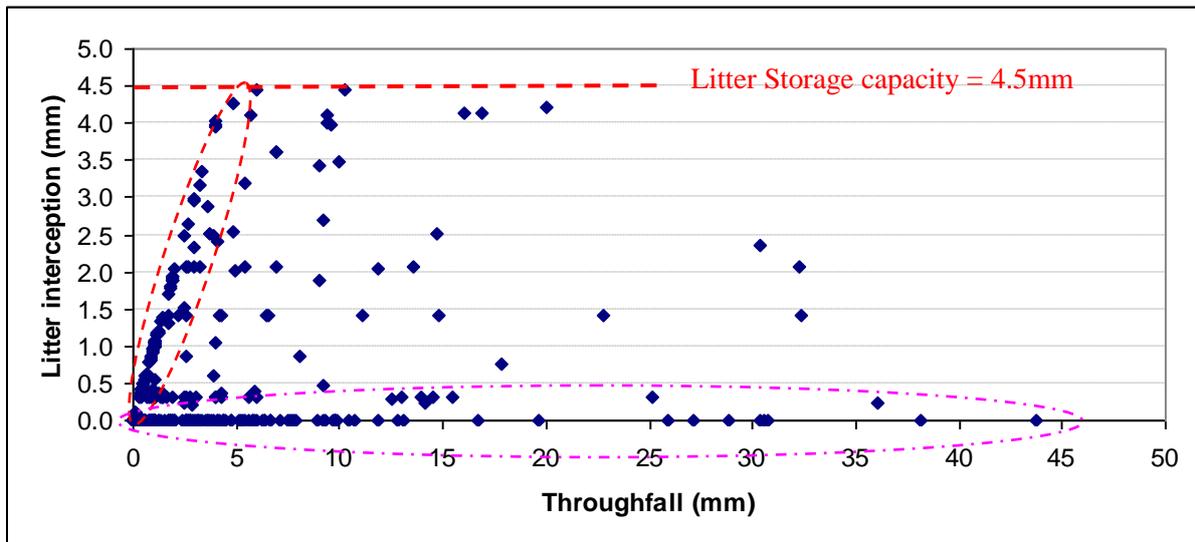
Figure 2.16   Observed litter interception by *Pinus patula* at Two Streams. The red circle represents increasing litter interception with increasing throughfall.

Figures 2.14 to 2.16 show the litter interception relative to the throughfall for *E. grandis, A. mearnsii* and *P. patula* respectively. The circled values closest to the y-axis represent the increasing litter interception with increasing throughfall. These are events that are smaller than the antecedent litter moisture deficit, and where almost 100% of the throughfall is intercepted. This happens until the point where the litter becomes saturated and maximum storage capacity is reached. Once the storage capacity has been reached, any additional throughfall will drain to the soil. The maximum litter storage capacities for *E. grandis, A. mearnsii* and *P. patula* are 2.6 mm, 1.8 mm and 4.5 mm respectively. The storage capacity is illustrated by the horizontal broken red line and was determined by analysing the data for events that occurred after a long dry period when the litter was completely dry and resulted in water draining out of the bottom of the litter interception basins (i.e. water that drained to the soil). The values circled along the x-axis are events that take place after the litter has been saturated (i.e. the storage capacity has been reached) and almost none of the throughfall is intercepted. The values scattered in between the two sets of circled values are events that exceed the antecedent litter moisture deficit, but where the litter is not completely dry, so the litter interception value will only be as large as the litter moisture deficit. Table 2.6 shows the total litter interception for *E. grandis, A. mearnsii* and *P. patula* during the study period.

Table 2.6   Observed litter interception by *E. grandis, A. mearnsii* and *P. patula*, from April 2008 to March 2011.

Species	Gross Precipitation (mm)	Observed litter interception (mm)	Observed litter interception (%)
E. grandis	1884.7	160.4	8.5
A. mearnsii	1884.7	124.7	6.6
P. patula	1909.7	231.2	12.1

From Table 2.6 it can be seen that during the period April 2008 to March 2011 the *P. patula* litter intercepted 231.2mm (12.1%) of gross precipitation, while *E. grandis* and *A. mearnsii* intercepted 160.4mm (8.5%) and 124.7mm (6.6%) of gross precipitation respectively. The litter interception results reported in this study may be slightly too high due to the potential errors reported in section 2.6.1.

3.3   Relative Contributions of Canopy and Litter Interception and Water that Drains to the Soil

Figures 2.17 to 2.19 illustrate the relative proportions of monthly gross precipitation that is intercepted by the canopy and litter as well as how much water drains to the soil (net precipitation) per month.
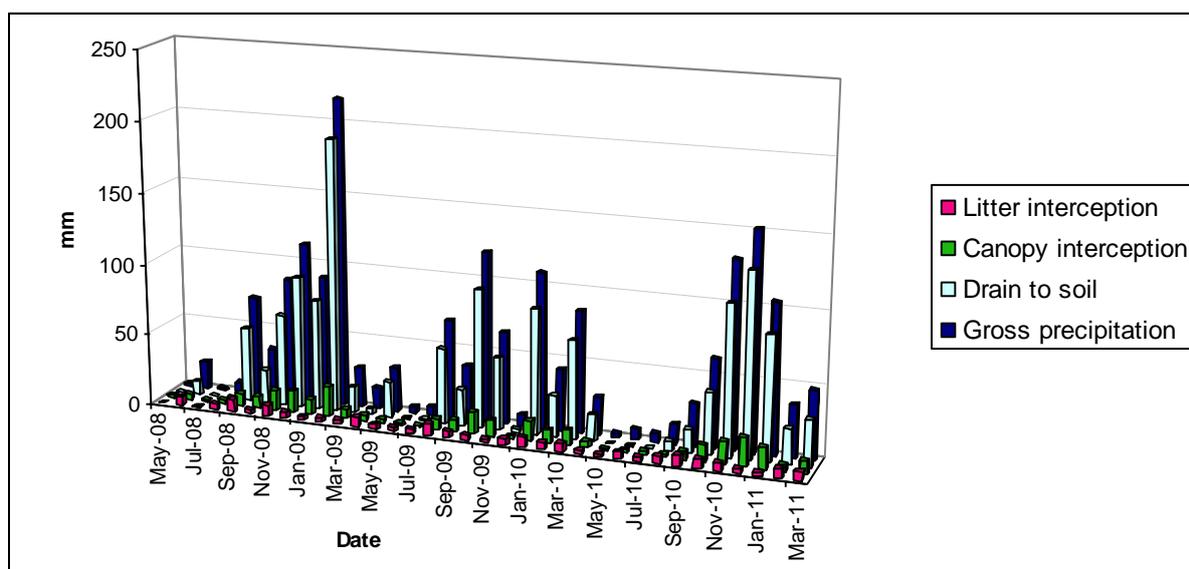
Figure 2.17   Comparison of monthly gross precipitation, water that drains to the soil, canopy interception and litter interception for *Eucalyptus grandis*.
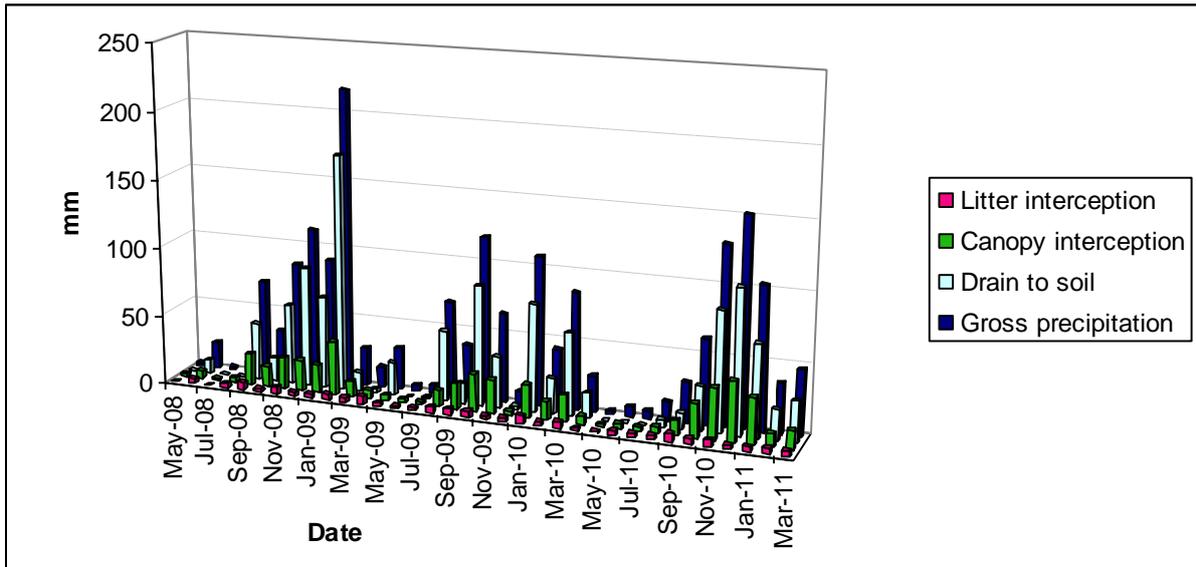
Figure 2.18   Comparison of monthly gross precipitation, water that drains to the soil, canopy interception and litter interception for *Acacia mearnsii*.
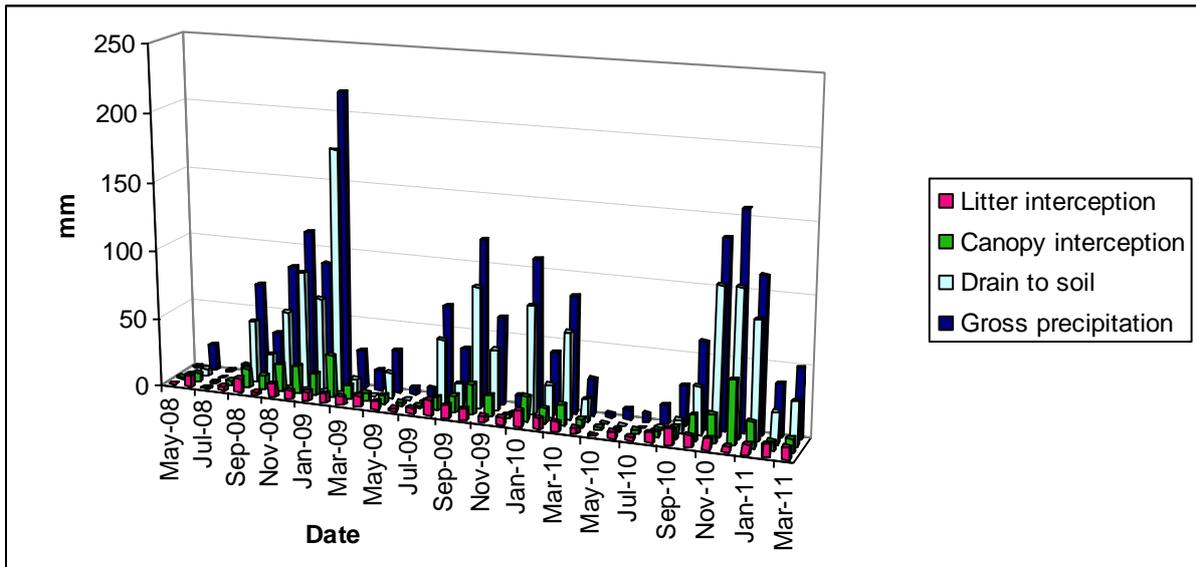
Figure 2.19   Comparison of monthly gross precipitation, water that drains to the soil, canopy interception and litter interception for *Pinus patula*.

From Figures 2.17 to 2.19, the three summer rainfall seasons over which this study took place can be identified, with February 2009 being the month with the highest rainfall of 216.4 mm. The relative contributions of canopy and litter interception to gross precipitation and therefore the amount of water that drains to the soil are dependant on the rainfall distribution. During the summer months, more water drains to the soil than is intercepted (canopy + litter). Conversely, during the winter months when there is little rainfall, there is often more rainfall intercepted than drains to the soil. The rainfall that does fall during the winter months is usually low intensity frontal rainfall and not a large amount,

resulting in a large proportion being intercepted by the canopy and litter. During the winter months, the litter often has time to dry out due to the extended periods of no rainfall, which results in a greater ability for the litter to intercept that which is not intercepted by the canopy during subsequent events. This will determine the amount of water that is available to drain to the soil. The total amount of water that drains to the soil during the study period is summarised in Table 2.7.

Table 2.7   Amount of water that drains to the soil for the study period April 2008 to March 2011 for *E. grandis*, *A. mearnsii* and *P. patula*

Species	Gross Precipitation (mm)	Observed water drained to soil (mm)	Observed water drained to soil (%)
E. grandis	1884.7	1437.0	76.2
A. mearnsii	1884.7	1237.7	65.7
P. patula	1909.7	1269.8	66.5

After canopy and litter interception have taken place, the remaining water drains to the soil (net precipitation). From Table 2.7 it can be seen that only 65.7% and 66.5% of gross precipitation reached the soil under the *A. mearnsii* and *P. patula* stands respectively. *Eucalyptus grandis* has the lowest combined interception losses and 76.2% of the gross precipitation reached the soil.

4.   DISCUSSION AND CONCLUSION

This study showed that interception plays a very important role in the forest hydrological cycle, with only 66.5% to 76.2% of gross precipitation being available water that drains to the soil, after the losses due to canopy and litter interception. Canopy interception by *E. grandis*, *A. mearnsii* and *P. patula* accounted for losses of 14.9%, 27.7% and 21.4% of gross precipitation respectively. Although litter interception resulted in a smaller portion of the total interception loss, it is none the less important. In this study it was found that litter interception accounted for a loss of 12.1% of gross precipitation by *P. patula*, and 8.5% and 6.6% for *E. grandis* and *A. mearnsii* respectively. Gerrits (2010) found litter interception to be as high as 22% in a beech forest, and 18% in a needle leaf litter Cedar forest, while Helvey (1964) found litter interception to be 34% in a poplar stand in the USA. Interception not only reduces net precipitation but it is also a threshold process, as a certain amount of water is required before successive processes such as infiltration and runoff can take place. These subsequent processes can only occur once the canopy and litter storage capacities have been reached and it can therefore be said that canopy and litter storage capacity are key factors in the control of canopy and litter interception. Although the storage capacity of the litter is much greater than that of the canopy,

canopy interception is greater. This highlights that the evaporative potential of the canopy is far greater than that of the forest floor litter due to its direct exposure to solar radiation and wind.

One implication of interception being a threshold process is that it causes a delay in the onset of subsequent processes, particularly infiltration (Gerrits, 2010). This delay may be a few seconds to minutes in cases where both the canopy and litter are near saturated or in high intensity storms. Conversely, this delay may be in the order of days to weeks in cases where the next rainfall event is not large enough to exceed the canopy and litter storage capacities, and therefore only after an event large enough to satisfy the combined storage capacities of the canopy and litter will subsequent processes take places. This is evident in Figures 2.14 to 2.16, where there are many events where the throughfall did not exceed the litter storage capacity and therefore no infiltration took place. This delay is also not the same for all species.

As interception reduces and delays subsequent hydrological processes differently for all species, it also determines the spatial distribution of net precipitation. Within a commercially afforested catchment such as the Mistley-Canema estate there are many species and types of vegetation and thus different canopy and litter interception characteristics. The spatial distribution of net precipitation is not only different between stands, but also within the stand. It is for this reason that linear troughs were used to measure throughfall as the throughfall varies from near the trunk to the edge of the canopy, depending on the structure and water holding characteristics of the canopy. Within a commercial plantation, the spacing and management of the trees will also affect the spatial distribution of throughfall. Therefore, interception plays a far more significant and complex role in a catchment water balance than just as a reducer of rainfall.

As the study site is situated in a mist belt area, where more than 50% of the daily rainfall events are less than 1mm, it is not surprising that the interception losses are high. As shown in Figure 2.13, the rainfall intensity affects the canopy storage capacity, and should not be considered as a constant. The canopy properties such as "wettability" and leaf angle also affect the water retention and therefore canopy storage capacity. Although, the *E. grandis* had the largest LAI, it has the lowest storage capacity. The rainfall amount, duration, frequency and intensity also play an important role in determining the canopy interception as shown in Table 2.5. It is therefore recommended that further research into canopy and litter interception be undertaken in other bioclimatic regions where rainfall patterns may differ. Furthermore, it can be seen from the results of this study that canopy and litter interception play a significant role in the water balance of a forested catchment and should not be ignored for water resources planning purposes. To account for canopy and litter interception loss for water resources planning, models that are not data intensive and that can make use of readily available data would improve and aid in decision making. The findings from this study could therefore be used in improving and verifying canopy and litter interception models.

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CHAPTER 3

Modelling canopy and litter interception in commercial forest plantations in South Africa

Modelling canopy and litter interception in commercial forest plantations in South Africa

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ABSTRACT

There is a gap in the knowledge of both canopy and litter interception in South African forest hydrology. Interception is typically considered to constitute only a small portion of the total evaporation and in some models is disregarded. Interception is a threshold process, as a certain amount of water is required before successive processes can take place. Therefore an error introduced in modelling interception, especially disregarding it, will automatically introduce errors in the calibration of subsequent models/processes. Field experiments to assess these processes, *viz.* canopy and litter interception were established for the three main commercial forestry genera in South Africa, namely, *Pinus, Acacia* and *Eucalyptus.* Drawing on both field and laboratory data, the "variable storage Gash" model for canopy interception and an idealised drying curve litter interception model were developed to represent these processes. It was found that canopy and litter interception can account for as much as 26.6% and 13.4% of gross precipitation respectively, and are therefore important hydrological processes. The models developed were able to adequately represent these interception processes and provide a way forward for more representative water resources planning modelling.

Keywords: Forest hydrology, Canopy, Litter, Interception, Model development.

1.   INTRODUCTION

There is a gap in the knowledge of both canopy and litter interception in South African forest hydrology, as well as internationally. Interception is typically considered to constitute only a small portion of total evaporation and in some models is disregarded completely (Gerrits *et al*., 2008) or merely lumped with total evaporation and not considered as a separate process (Savenije, 2004).

Interception is a threshold process, as a certain amount of water is required before successive processes such as infiltration and runoff can take place. Therefore an error introduced in modelling interception, especially disregarding it, will automatically introduce errors in the calibration of subsequent models/processes (Savenije, 2004).

The first reference to the development of canopy interception models in current literature can be ascribed to Horton (1919) who defined interception loss as "leaf storage capacity and evaporation loss during the storm" which he expressed as:

$$I_l = \mathrm{E}dt + \mathrm{S}_c \qquad\qquad (3.1)$$

Where:

E	=	evaporation rate of intercepted water during rainfall,
S_c	=	canopy storage capacity, and
t	=	rainfall duration.

Until the early 1970's, attempts to generalise interception losses were usually expressed in the form of regression analyses of interception loss and bulk rainfall (Llorens, 1997).

Rutter *et al.*, (1971, 1975) were the first to model forest rainfall interception with a physically based model using hourly rainfall and meteorological data (Llorens, 1997), having recognised that the process was primarily driven by evaporation from the wetted canopy. The evaporation from the wet canopy is calculated using the Penman-Monteith equation with the canopy resistance set as zero (Rutter, 1971). The canopy structure is described by the throughfall coefficient (*p*), the stemflow partitioning coefficient (*p_t*), the canopy storage (*S_c*) and the trunk storage (*S_t*). The throughfall, stemflow and interception loss is estimated in the model using input rainfall and meteorological data (Rutter, 1971; Valente *et al.*, 1997) The model is essentially based on the dynamic calculation of the water balance of the canopy and trunk through Equations 3.2 and 3.3.

$$(1 - p - p_t)\int P dt = \int D dt + \int E dt + \Delta C \qquad\qquad (3.2)$$

$$p_t \int R dt = Sf + \int E_t dt + \Delta C_t \qquad\qquad (3.3)$$

Where *R* is the intensity of gross rainfall, *D* is the rate of drainage from the canopy, *E* is the rate of evaporation of water intercepted by the canopy, *ΔC* is the change in canopy storage, *Sf* is stemflow, *E_t* is the evaporation of water intercepted by the trunk, and *ΔC_t* is the change in trunk storage.

Later, Gash (1979) proposed a rainfall interception model, which is essentially a simplified analytical form of the Rutter *et al.,* (1971, 1975) model. While Gash (1979) recognised that Rutter's model was the most rigorous method for estimating interception loss at the time, he identified practical disadvantages in its use. Firstly, it requires detailed meteorological data and, secondly, it was computationally intensive. These two problems are however, not so significant today, as data collection and computational processing have advanced considerably (Llorens, 1997).

The original Gash (1979) model is based on three main components;
1. the bulk rainfall input,
2. canopy structure parameters, and
3. evaporation of intercepted water.

The model is also based on three main assumptions, as follows;
1. the rainfall pattern is represented by a series of discrete storms which are separated by sufficiently long intervals to allow the canopy to dry,
2. the rainfall and evaporation rates are constant during the storm, and under conditions of canopy saturation the mean rainfall and evaporation rates are used, and
3. there is only one storm per rain day (which is a definite weakness of the model).

The original Gash (1979) model considers rainfall as a series of discrete events, during which three phases can be identified. These are the wetting phase, saturation phase, and the drying phase after the rainfall has stopped.

The meteorological conditions prevailing during the first two phases are assumed to be the same and average values of gross rainfall intensity (R) and evaporation rate (E) for saturated canopy conditions are calculated for the whole simulation period and then applied in a generalised form to all individual rainfall events (Valente *et al*., 1997). The model uses total daily rainfall and assumes that there is only one storm per day and that there is sufficient time between storms for the canopy to dry (Zhang *et al*., 2006) in its calculation of canopy interception. The model was therefore not intended for use on short crops in temperate regions where the vegetation may stay wet for prolonged periods of time (van Dijk and Bruijnzeel, 2001a). Like the Rutter model, Gash's analytical model requires prior estimates of structural parameters of the forest canopy which are described in terms of the storage capacity (S_c), which is the amount of water left on a saturated canopy under conditions of zero evaporation after the rainfall and canopy drainage have ceased (Gash and Morton, 1978). The model also requires a free throughfall coefficient (p) and a stemflow coefficient (p_t). The Gash model has been used with considerable success to predict interception in a wide range of environments, including temperate coniferous and broadleaf forests, and tropical forests (van Dijk and Bruijnzeel, 2001a).

However, both the original Rutter *et al.*, (1971, 1975) and Gash (1979) models only performed well for modelling interception in relatively closed canopies. This is especially true for the evaporative process, due to the assumption that the canopy and trunk storages extend to the whole plot area. Results from various studies (Lankreijer *et al.*, 1993; Gash *et al.*, 1995) suggest that the models should not be applied to sparse forests as the models tend to overestimate the interception loss. This led to the development of a 'sparse canopy' variant (Gash *et al.*, 1995) in which evaporation from a wet canopy was considered linearly dependant on the canopy cover fraction (van Dijk and Bruijnzeel, 2001a).

Gash *et al.,* (1995) revised the original model by addressing both a conceptual error and its poor performance in sparse canopy forests. This was corrected by introducing an additional parameter for the canopy cover fraction (c) as well as making the canopy storage (S_c) and the wet canopy evaporation rate linearly dependant on it. By doing this the conceptual error was removed, as it was assumed in the original model that the relative evaporation rate (E/R) was independent of (1-p-p_t). Had this not been corrected, a negative algorithm would result when calculating the rainfall necessary to saturate the canopy (P'_G), in a situation where (1-p-p_t)R<E (Gash *et al.*, 1995). Recent applications of the model indicate that it is suitable for predicting a wide range of conditions, from closed canopies to sparse canopies (David *et al.*, 2005).

Van Dijk and Bruijnzeel (2001a, 2001b) then modified the Gash *et al.,* (1995) revised model by allowing it to be applied to rapidly growing vegetation where the leaf area index (LAI) is changing through time. The modifications are based on the following three hypotheses:

1. The canopy capacity (S_c) is linearly related to LAI.
2. The relative evaporation rate (E/R) can be expressed as a function of LAI.
3. The water that is retained on the stems can be treated in a similar way to that retained by the canopy. (i.e. evaporation from saturated stems during the storm may be included in the simulations).

The modifications by van Dijk and Bruijnzeel (2001a, 2001b) to the Gash *et al.*, (1995) model essentially revolve around the leaf area index (LAI) parameter. For this model LAI is defined as the cumulative one-sided area of (healthy) leaves per unit area. LAI and the canopy cover fraction (c), can be related to one another via the Beer-Lambert equation that describes the attenuation of radiation (e.g. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate through leaves much, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between *c* and LAI is thus given by Equation 3.4

$$c = 1\text{-}e^{\text{-}K.LAI} \tag{3.4}$$

Where K is the extinction coefficient. The value of K for a particular radiation wavelength depends on the inclination angle and distribution of the leaves, and for PAR usually ranges between 0.6 and 0.8 in forests (van Dijk and Bruijnzeel, 2001a, 2001b).

A shortcoming of previous versions of the Gash model is that they consider the canopy storage capacity to be constant. As the results in Chapter 2 show, the storage capacity varies with rainfall intensity and has been corroborated by Calder (1996) and Hall (2003), a canopy interception model that considers a variable storage capacity with rainfall intensity is required. With this in mind, the "variable storage Gash model" was developed. The results from the "variable storage Gash model" were used as an input to model litter interception, as it is the throughfall that determines the amount of water that will reach the litter. Unlike canopy interception which is dependent on many factors including the storage capacity, potential evaporation, rainfall intensity and rainfall duration, the litter interception is largely dependent on the storage capacity. This is due to evaporative drivers under the canopy such as radiation, temperature and wind speed being moderated by the above canopy. Therefore, as long as the input of simulated throughfall from the "variable storage Gash model" and litter storage capacity is estimated accurately, then the idealised drying curve model should perform well. While the "variable storage Gash model" may be considered complex and the idealised drying curves fairly simple, it is important to develop models that are useful at the scale of implementation and can use readily available data. A way of negotiating complex problems is by considering a requisite simplicity. A requisite simplicity attempts to discard some detail, while retaining conceptual clarity and scientific rigour (Stirzaker *et al*., 2010). Therefore, by combining the "variable storage Gash model" and the idealised drying curves to simulate "total interception" a requisite simplicity is achieved.

In order to provide further insight into these processes, field experiments to assess canopy and litter interception were established for the three main commercial forestry genera in South Africa, namely, *Pinus, Acacia* and *Eucalyptus* to assess interception of "broadleaf", "compound leaf" and "needle-leaf" trees. The study took place in the well documented CSIR Two Streams research catchment, located in the Seven Oaks area, about 70km north-east of Pietermaritzburg in the KwaZulu-Natal Midlands. In this paper we show how information from these studies can be used to improve the representation of interception in hydrological models. The field data collected, as well as laboratory data were used to improve modelling these two important hydrological processes, using as few parameters as possible but retaining a requisite simplicity.

2. VARIABLE STORAGE GASH INTERCEPTION MODEL

The original Gash (1979) and later the revised Gash *et al*., (1995) model are probably the best known canopy interception models. Both the Gash (1979) and revised Gash *et al*., (1995) models classify storms according to the amount of gross rainfall (P_g) generated and then compute interception loss (I), throughfall (T), and stemflow (*Sf*). The Gash (1979), Gash *et al*., 1995) models, and subsequently the "variable storage Gash model" which has been developed for this study, require canopy structure parameters, climate parameters, and interception parameters.

The "variable storage Gash model" is based on three assumptions, the first two being from the original Gash model:

1)   The rainfall distribution pattern may be represented as a succession of discrete storms, separated by sufficiently long periods to allow the canopy and trunks to dry (Gash, 1979, Gash *et al*., 1995);

2)   The rainfall and evaporation rates are constant during each storm and may be considered as constant between several storms during the same period (Gash, 1979, Gash *et al*., 1995); but introduces an additional assumption i.e. that,

3)   The maximum canopy storage capacity (S_c^{max}) is linearly related to LAI (van Dijk and Bruinzeel, 2001a, 2001b), but the storage capacity (S_c) varies with different rainfall intensites (R).

The integrity of the original Gash model has not been jeopardised by the modifications made to the "variable storage Gash model". The process of interception loss is a function of several properties of the tree, including branch, stem and crown characteristics, and the structure of the stand (Rutter *et al*., 1975). Widely spaced trees have larger spaces between them, therefore the ventilation within the stand increases and may result in more rainfall being intercepted and evaporated from the tree. However, tree spacing also affects the leaf area per unit ground area and the spatial distribution of leaf area density and will modify both the available energy and boundary layer conductance of the stand and thus influence the rate of evaporation of intercepted water (McNaughton and Jarvis, 1983) in (Teklehaimanot *et al*., 1991). In the "variable storage Gash model" this has been accounted for by using LAI as the primary parameter to describe the canopy structure. The model requires just five parameters to describe canopy interception, and seven if stemflow is required i.e. gross precipitation, evaporation, rainfall rate and LAI and maximum storage capacity. For stemflow, the additional parameters are trunk storage capacity (S_t) and the stemflow partitioning coefficient (p_t). Table 3.1 summarizes the names of the various versions of the Gash models and authors referred to in this document.

Table 3.1   Evolution of the various versions of the Gash model referred to in this document.

AUTHOR	NAME OF MODEL
Gash (1979)	Original Gash model
Gash *et al.*, (1995)	Revised Gash model
Van Dijk and Bruijnzeel (2001)	Modified Gash model
Bulcock and Jewitt (2011)	Variable storage Gash model

2.1   Interception Parameters

One of the most important parameters in all versions of the Gash model, including the "variable storage Gash model" is the rain to fill canopy storage ($P'g$) which is described by Equation 3.5:

$$P'g = -\ln\left(1 - \left\{E/\left[R(1 - p - pt)\right]\right\}\right) \cdot S_c\left(R/E\right) \tag{3.5}$$

In this equation, the main term is the $S_c(R/E)$ term, which is the amount of rain needed to fill the storage given, that most of the rain passes through the tree canopy. It must be noted that it must be impossible for $E/R > (1-p-pt)$, because ($1-p-pt$) equals interception *and* canopy drip throughfall, whereas E/R is only interception.

The rain to fill the trunk storage ($P't$) (Gash, 1979) is described by Equation 3.6:

$$P't = S_t/p_t. \tag{3.6}$$

The stemflow partitioning coefficient (p_t) is the fraction of rain that runs down the stem of a tree during a storm, and the trunk storage capacity (S_t) is the total amount of water the trunk can hold (mm). The intercepted coefficient is therefore the fraction of rain held in the canopy during a storm and is described as ($1-p-p_t$).

2.2   Analytical Model Equations

The equations in the original Gash (1979), revised Gash *et al*., (1995) and "variable storage Gash" models used to distribute rainfall from individual storms between the different storage terms are described below. Some are constant for all storms while others depend on the actual rainfall amount.

For small storms, where the rainfall amount is insufficient to saturate the canopy (i.e. $Pg<P'g$), the evaporation from the canopy (I_c) is described as Equation 3.7:

$$I_c = Pg(1 - p - p_t) \qquad (3.7)$$

For large storms (i.e. $Pg>P'g$), evaporation is considered in four phases (Equation 3.8 to 3.11):

Evaporation during wetting phase
$$(I_w) = [(1 - p - pt)P'g)] - S_c \qquad (3.8)$$

Evaporation of saturated canopy
$$(I_s) = (E/R)(Pg - P'g) \qquad (3.9)$$

Evaporation after rain ceases
$$(I_a) = S_c \qquad (3.10)$$

Evaporation from trunks
$$(I_t) = St \quad (\text{if } Pg<P't, \text{ then } It=p_t.Pg) \qquad (3.11)$$

For all storms, irrespective of size, the stemflow (F) (Equation 3.12) and throughfall (T) (Equation 3.13) are considered as:

$$Sf = pt(Pg - P't) \qquad (3.12)$$

$$T = Pg - I - Sf \qquad (4.13)$$

The stemflow is the product of the stemflow partitioning coefficient (*pt*) and the difference between gross precipitation and rain to fill the trunk storage. Throughfall is simply the difference of gross precipitation, interception loss and stemflow.

2.3 Canopy Structure Parameters

Gash *et al.*, (1995) introduced the canopy cover fraction (*c*) to account for inadequacies in modelling sparse canopies in the original model. Van Dijk and Bruijnzeel (2001a, 2001b) then modified the revised Gash *et al.*, (1995) model allowing it to be applied to rapidly growing vegetation where the LAI is changing through time. In addition, the "variable storage Gash model" introduces a vegetation/species specific parameter, termed the maximum elemental volume (v_e^{max}), which accounts for the water holding characteristics of the canopy. LAI is defined as the cumulative one-sided area of leaves per unit area. In this model, LAI and *c*, can be related to one another via the Beer-Lambert equation (Equation 3.14) which describes the attenuation of radiation (i.e. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate far through leaves, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between *c* and LAI is thus given by Equation 3.14 and is illustrated in Figure 3.1, where the extinction coefficient *k* = 0.5 (Landsberg and Waring, 1997; Battaglia *et al.*, 2004) was used to model the results in this study. Gazarini *et al.*, (1990) found that a value of *k* = 0.50 was appropriate in their study of *E. globulus*, while Pierce and Running (1988) and Sampson and Lee Allen (1998) used values of 0.52 and 0.60 for pine respectively. No values for *Acacia* could be found.

$$c = 1\text{-}e^{-k.\text{LAI}} \quad\quad\quad\quad\quad (3.14)$$
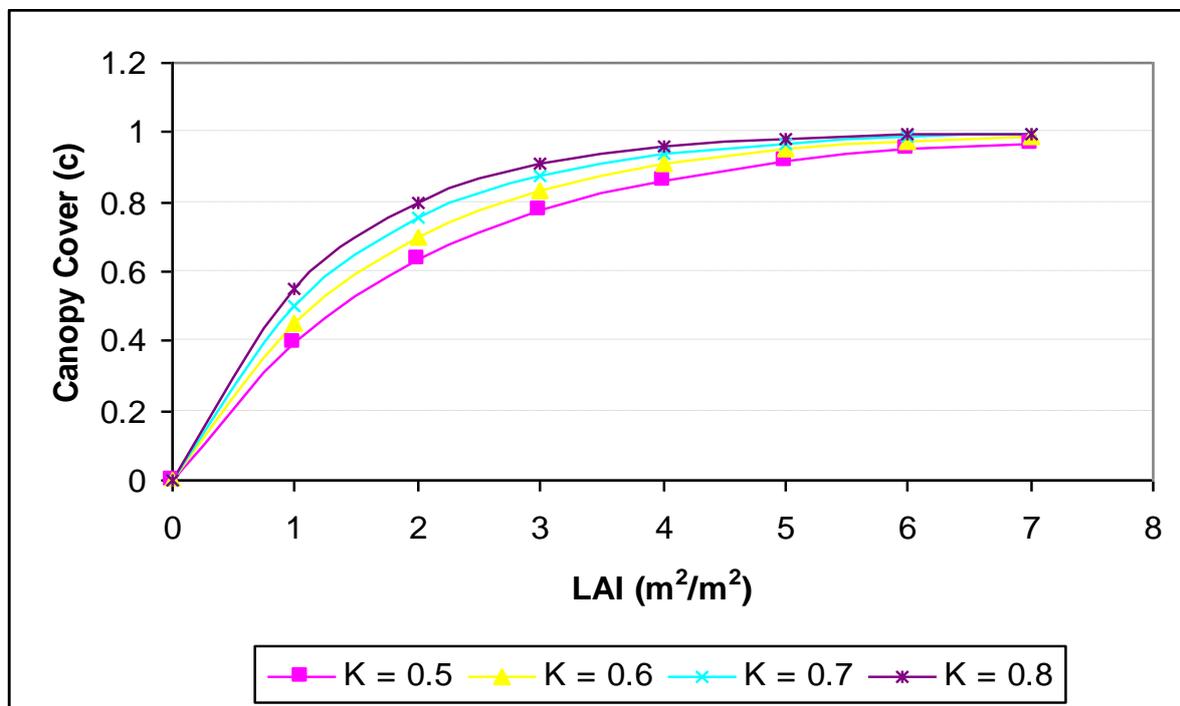
Figure 3.1   Beer-Lambert canopy cover curves for different extinction coefficients.

The free throughfall coefficient (*p*) is the fraction of rain that passes through a canopy during a storm without touching the canopy and can be described as *p* = 1-*c* (van Dijk and Bruijnzeel, 2001a).

2.4   Storage Capacity and Drop Size

An often ignored factor when modelling or measuring canopy interception which has been incorporated into the "variable storage Gash model" is that of drop size. The importance of drop size when determining canopy interception losses was first established through experimental work in the tropical climates of Indonesia and India by Calder (1986). Calder (1986) developed a stochastic interception model that predicts that for storms with the same total rainfall, interception losses would be larger for those with smaller drop sizes. The model also considers the drop retention by the canopy, and is partially dependent on the kinetic energy and hence drop size. The ability of a canopy to retain rain drops is parameterised in the model by q, the drop retention number. The drop retention is dependent upon the size and kinetic energy of the impacting drop, as well as canopy properties such as 'wettability' and leaf angle (Hall, 2003).

To incorporate the dependence of q on both drop volume and therefore kinetic energy into the model, a vegetation/species specific parameter is introduced, termed the maximum elemental volume (v_e^{max}) and is expressed in Equation 3.15. This is calculated by considering drops impacting the surface with a kinetic energy as close to zero as possible to determine the maximum storage capacity (S_c^{max}), which according to Calder (1996) are events with an intensity of less than 0.36 mm.h^{-1} (*cf.* Chapter 2) and the LAI. The v_e^{max} values used in this study are as follows:

- *Eucalyptus grandis* = 0.24
- *Acacia mearnsii* = 0.63
- *Pinus patula* = 0.51

$$v_e^{max} = q.v_0 \text{ (i.e. } q = \frac{v_e^{max}}{v_0})$$
(3.15)

where:

q   -   drop retention

v_e^{max} -   is the maximum volume of water retained by a canopy element (mm^3), and

v_0 -   is the mean volume of the rain drop (mm^3) with almost zero kinetic energy.

The term maximum storage capacity (S_c^{max}) which is obtained when the canopy is wetted with drops of almost "zero" kinetic energy and is defined as:

$$S_c^{max} = v_e^{max}.\text{LAI} = q.v_0.\text{LAI}$$
(3.16)

The storage capacity (S_c) for non-zero kinetic energy drops can therefore be defined as:

$$S_c = v_e.\text{LAI} = q.v.\text{LAI} \tag{3.17}$$

The drop volume (v) is estimated using the Marshall-Palmer (1948) equation:

$$v = a.R^b \tag{3.18}$$

where parameters $a = 0.124$, $b = 0.63$, and

R -   Rainfall rate or intensity (mm.h^{-1}).

In order to operate the model for a particular vegetation type requires values for two vegetation specific parameters S_c^{max} and v_e^{max}. A functional relationship between S_c/S_c^{max} (equations 3.19a and 3.19b) and v is also required. Calder (1996) developed the following empirical exponential relationship from rainfall simulator experiments:

$$S_c/S_c^{max} = 1 \qquad\qquad \text{for } v < 0.065 \tag{3.19a}$$
$$S_c/S_c^{max} = 0.5 + 0.73.\exp(-5.5.v) \qquad \text{for } v > 0.065 \tag{3.19b}$$

Then, rearranging the Marshall-Palmer (1948) equation to determine R for $v < 0.065$ it can be established that $S_c/S_c^{max} = 1$ for $R < 0.36$ mm.h^{-1}. From field measurements of leaf area index and storage capacity for events with $R < 0.36$ mm.h^{-1}, the vegetation/species specific v_e^{max} can be calculated. By knowing the v from the Marshall-Palmer (1948) equation and S_c^{max}, the variable S_c can be calculated as the product of S_c/S_c^{max} and S_c^{max}.

The maximum elemental volume (v_e^{max}) does not change with the growth of the tree due to the linear relationship between S_c^{max} and LAI. The linear relationship between storage capacity and LAI for a given vegetation type of constant physiognomy and configuration has been corroborated by the results of Aston (1979), Von-Hoyningen-Huene (1981), Pitman (1989), Liu, (1998) and van Dijk and Bruijnzeel (2001).

2.5   Climatic Parameters

The climatic parameters required for the "variable storage Gash model" are, gross precipitation (P_g), mean rainfall rate (R) and mean evaporation rate (E) per event. In this study the Penman-Monteith reference potential evaporation was used with the stomatal resistance term (r_s) equal to zero for the period that the rainfall event took place.

3.   LITTER INTERCEPTION MODEL

A smaller, although significant role is played by litter interception. According to Schaap and Bouten (1997) in their study of a Douglas fir stand, as much as half of the total forest evaporation may originate from the canopy and litter interception processes. The water holding capacity of the surface horizon depends on the surface area of the material, similar to the storage of the foliage. Researchers have shown that litter interception is governed primarily by the moisture holding capacity and initial storage capacity of the litter, but also by the evaporative demand following the rainfall event (Rowe, 1955, Helvey and Patric, 1965). Throughfall that reaches the dry litter gradually increases the litter moisture to field capacity and then saturation. The saturated litter can lose as much as 75% of its moisture in the first four days of drying (Blow, 1955 and Jacobsz, 1987) and reaches an equilibrium after 10 to 12 days (Metz, 1958). Based on these considerations and field observations, the litter interception model was developed.

3.1   Litter Model Conceptualization

The litter interception model is based on the drying curves of *E. grandis, A. mearnsii and P. patula*, developed from samples collected at the Two Streams study site. A drying curve for naturally drying litter samples is determined from calculations of moisture content in the litter in the days following a saturating rainfall event following the approach of Jewitt (1991). A representative sample of the litter was collected for each of the three genera and placed in an aluminium foil tray that had holes punched into it to allow for free drainage of water. The samples were then dried in an oven overnight at 100°C for 24 hours. Once the samples were dried, they were weighed. They were then saturated and weighed again to obtain the litter storage capacity as shown in Table 3.2. The samples were then weighed daily for twelve days. This process was repeated twice annually for the three years of the study, to obtain the idealized drying curves illustrated in Figure 3.2. The drying curves were derived from samples dried in the laboratory and under a shaded outdoor area.
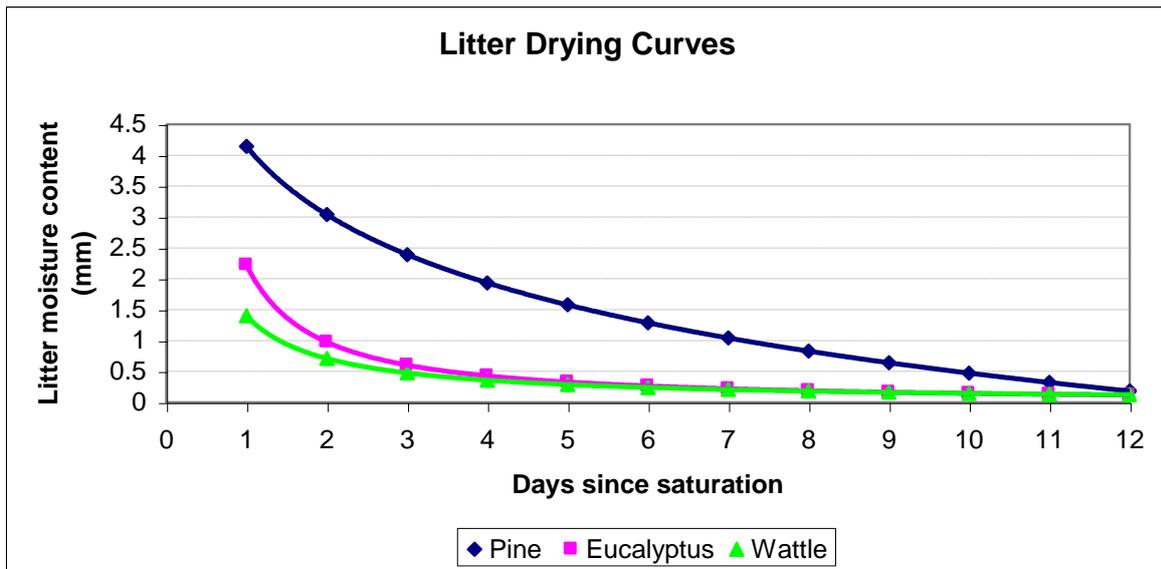
Figure 3.2   Idealised drying curves derived from laboratory experiments for three litter types in the KZN midlands.

The drying curve equations, litter storage capacity and litter thickness for each of the three genera are summarized in Table 3.2.

Table 3.2   Drying curve equations and litter storage capacity derived from laboratory experiments for three litter types in the KZN Midlands

Species	Drying curve equations	Litter storage capacity (mm)	Litter thickness (mm)
E. grandis	$y = 2.2202.(x)^{-1.1879}$	2.6	38
A. mearnsii	$y = 1.40.(x)^{-0.983}$	1.8	20
P. patula	$y = -1.5935.\ln(x) + 4.1419$	4.5	97

The litter model, which is programmed in a Microsoft® Excel spreadsheet, is site specific, as the litter characteristics will vary between species, age and climatic region. The model uses the daily throughfall simulated using the "variable storage Gash model" as an input. A "bookkeeping" method is then used to calculate the litter moisture content depending on the preceding dry days following the wetting of the litter from the drying curves in Table 3.2. Once saturation (storage capacity) is reached, any excess throughfall will infiltrate to the soil.

4.   STUDY SITE

The Mistley-Canema estate is situated in the Seven Oaks district in the KwaZulu-Natal Midlands, South Africa as shown in Figure 2.1 (*cf.* Chapter 2, Section 2.1). The climate is humid, with an annual rainfall ranging from 800mm to 1280mm per annum and the mean annual temperature is 17°C. Commercial afforestation has long been practiced in the area and is the most widespread land use, with gum (*Eucalyptus*), pine (*Pinus*) and wattle (*Acacia*) being the genera of choice. Sugarcane is also grown at sites where drainage of cold air is good, ensuring that no frost or only light frost may occur (Everson *et al*., 2006). In this study, 5 year old *Eucalyptus grandis* and *Acacia mearnsii*, as well as 16 year old *Pinus patula* stands with LAI values of 2.7, 2.3, and 1.9 respectively were considered.

5.   FIELD DATA COLLECTION

Gross precipitation and evaporation data were supplied by the CSIR from two automatic weather stations forming part of an ongoing Water Research Commission (WRC) project (Everson *et al*., 2006). One was for the *A. mearnsii* and *E. grandis* which is situated on a tower above the canopy and the other for the *P. patula* site is situated in the open, but not above the canopy, but is closer to the study site. In order to validate the models, canopy and litter interception data was collected from April 2008 to March 2011. Data from September 1998 to March 2011 was then used to model canopy and litter interception for almost a thirteen year period.

5.1   Throughfall and Canopy Interception Measurements

Throughfall measurements were undertaken using a nest of three "V" shaped troughs based on the design of Cuartus *et al*., (2007) constructed from galvanised sheeting. The dimensions of each trough are 10 cm wide x 200 cm long. Conventional "U" or "V" shaped troughs are susceptible to blockage by fallen debris and water loss from splash out, however, this system minimizes splash out by using steep "V" shaped sides. The troughs were covered with mosquito netting to minimize the entry of debris, which reduces the demand of cleaning and maintaining the system. The troughs were then connected to a tipping bucket gauge and an event data logger. Because the trough represents a linear and continuous sampling surface, the length scale variation of leaves, branches, and tree crown, it is assumed to be a representative integral of the throughfall caught (Cuartus *et al*., (2007). During the study period, canopy interception accounted for more between 14.9% and 27.7% of gross precipitation.

5.2   Litter Interception and Water Drained to Soil Measurements

The litter interception and water that drains to the soil was measured using two round galvanized iron basins that fit into each other. The upper basin which had a diameter of 0.5 m and was filled with litter and had a geotextile lining on top of a wire mesh base, so water can percolate into the lower basin (*cf*. Chapter 2, Section 2.6). The water that was collected in the lower basin drains into a tipping bucket and records the water that would have drained to the soil. The litter interception was then calculated as the difference between throughfall and the water that drained to the soil. The amount of litter interception measured was about 12.1% for *P. patula,* 8.5% for *E. grandis*, and 6.6% for *A. mearnsii*.

6.   RESULTS AND DISCUSSION

6.1   Canopy Interception

The importance of canopy and litter interception in the water balance of a forested catchment are illustrated in Figures 3.3 and 3.5 from the observed and modelled results of this study. The canopy and litter interception data collected during the study period were used to validate the models. Canopy and litter interception were then modelled using historical rainfall and evaporation data obtained from the CSIR from September 1998 to March 2011. The parameters used in validating the models during the study period from April 2008 to March 2011 were kept constant, with only the rainfall and evaporation data changing when modelling from September 1998 to March 2011.
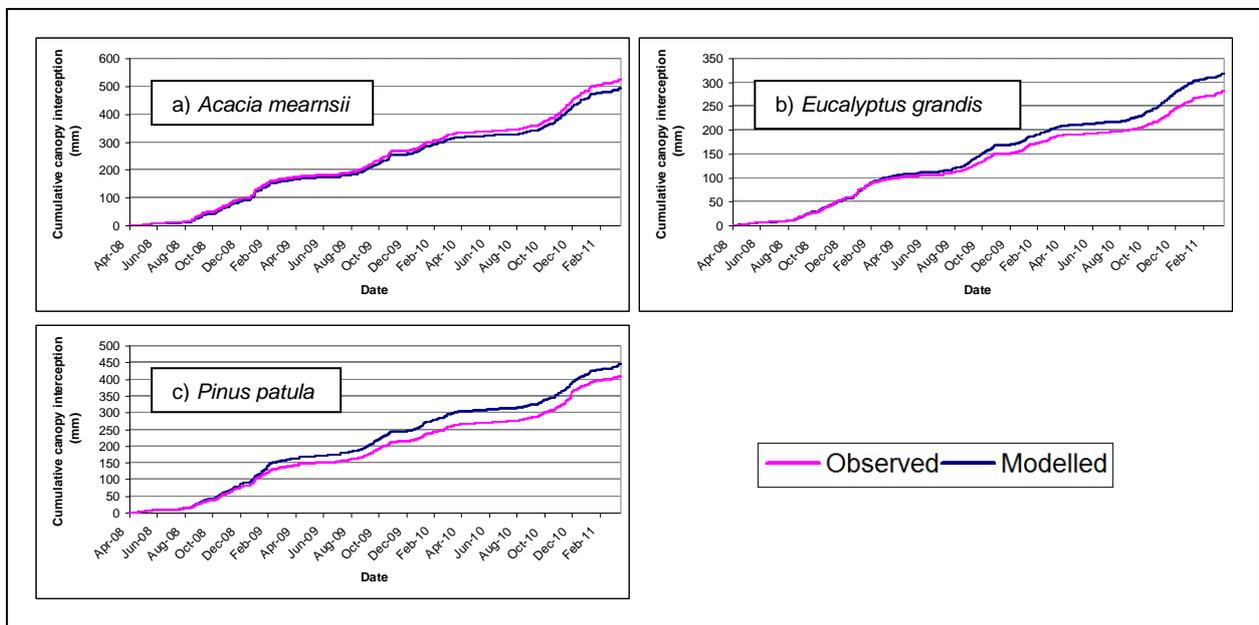
Figure 3.3   Cumulative observed and modelled canopy interception simulated with the "variable storage Gash model" from April 2008 to March 2011 at Two Streams.

The results of this study show that the modelled canopy interception ranges from 16.9% to 26.6% for *E. grandis* and *A. mearnsii* respectively, and *P. patula* with 23.3% of gross precipitation being intercepted. Figures 3.3a,b and c illustrate that the modelled *E. grandis, A. mearnsii* and *P. patula* canopy interception results summarized in Table 3.3 corresponded well with the observed data, with the difference between the modelled and observed ranging between 1.1% and 2.0%. This corresponds to an relative error of between 4.0% and 13.4% between modelled and observed results.

Table 3.3   Summary of observed and modelled canopy interception results for April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed canopy interception (mm)	Observed canopy interception (%)	Modelled canopy interception (mm)	Modelled canopy interception (%)	Relative Error (%)
Eucalyptus	1884.7	280.4	14.9	318.4	16.9	13.4
Acacia	1884.7	522.4	27.7	501.4	26.6	4.0
Pinus	1909.7	408.7	21.4	444.1	23.3	8.9

Rainfall interception from the canopy was responsible for a large amount of the total evaporation from a forested catchment, and perhaps more than many may anticipate, as shown in Table 3.3. A noticeable result is that *Eucalyptus grandis* has the lowest interception of the three species in this study even though it has the highest LAI. The small difference between the observed and modelled canopy interception can therefore be largely attributed to the successful estimation of the canopy storage capacity. While *E. grandis* has the highest LAI, it also had the smallest elemental volume (v_e) and canopy retention (q), therefore having the smallest canopy storage capacity. It is therefore important to consider the retention characteristics of the canopy when modelling canopy interception and not just base the estimation of the canopy storage capacity on LAI. Furthermore, the estimation of canopy storage capacity took the rainfall intensity into account, which was an important consideration in a mistbelt area where there are a large number of low intensity events, but the bulk of the rainfall comes from the relatively few large, high intensity storms. From Figure 3.4 it can be seen that 50.8% of the rainfall events during this study period were less than 1 mm.day^{-1}, with 10.9% and 7.4% of the events being between 1 and 2 mm and 2 and 3 mm respectively. The rainfall record from September 1998 to March 2011 showed a very similar trend in the rainfall distribution to that recorded during the study period. This indicates that the rainfall during the study period was typical for the catchment. In these small events almost 100% of the gross rainfall would be intercepted by the canopy and the remainder by the litter (Jacobsz, 1987). It must be noted that the raingauges did not have a mist interceptor, but any mist captured by the canopy would be accounted for by throughfall if there is a rainfall event that occurs after the canopy has been wetted by mist (i.e. that canopy storage capacity has been partially or fully filled by the mist interception), so the interception amount may in fact be slightly underestimated.
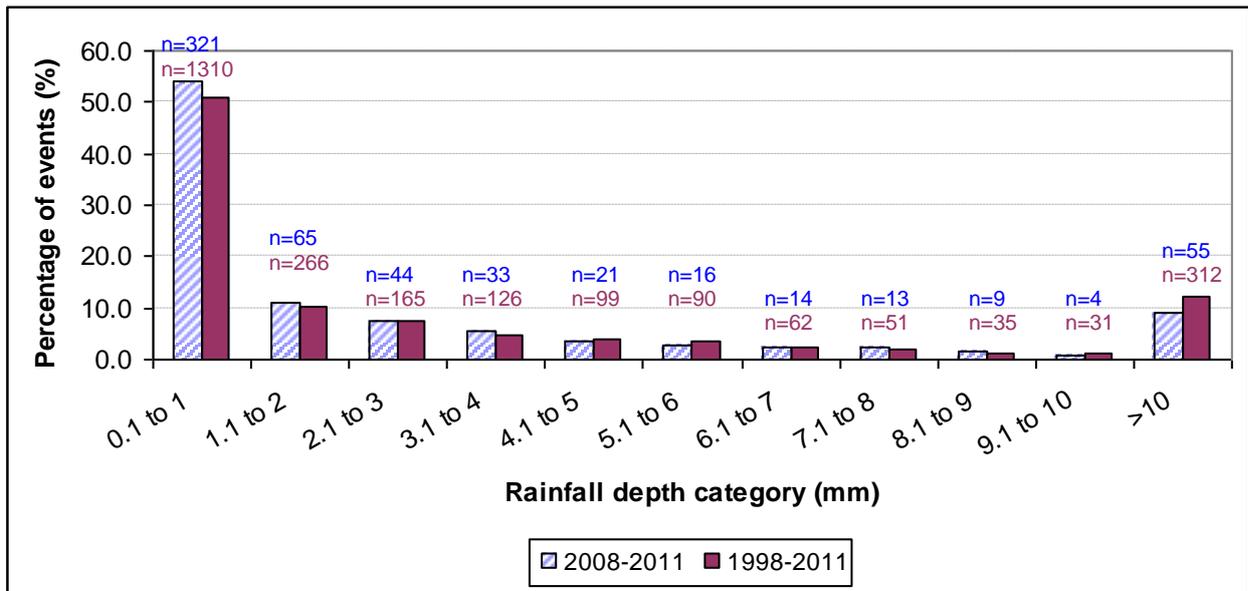
Figure 3.4   Percentage of rainfall events per rainfall depth category (n=595 and n=2577) for the periods April 2008 to March 2011and September 1998 to March 2011 respectively.

The performance of the "variable storage Gash model" in comparison with the observed data for the period April 2008 to March 2011 is summarised in Table 3.4.

Table 3.4   Summary of "variable storage Gash model" and observed canopy interception statistics for the period April 2008 to March 2011.

Statistic	Eucalyptus grandis		Acacia mearnsii		Pinus patula	
	Modelled	Observed	Modelled	Observed	Modelled	Observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	0.30	0.26	0.47	0.49	0.42	0.38
Standard Error (mm)	0.015	0.014	0.029	0.030	0.022	0.025
Standard Deviation (mm)	0.48	0.44	0.93	0.97	0.72	0.81
Sample Variance (mm)	0.23	0.19	0.86	0.95	0.52	0.64
RMSE	0.24		0.26		0.54	
R^2	0.76		0.83		0.56	

From Table 3.4 it can be seen that the descriptive statistics for observed and modelled canopy interception correspond well. The worst performing being *P. patula* with a R^2 and Root Mean Square Error (RMSE) of 0.56 and 0.54 respectively. The R^2 for *E. grandis* and *A. mearnsii* are 0.76 and 0.83 respectively, as well as low RMSE values of 0.24 and 0.26 indicating that the model performed well.

6.2   Litter Interception

The results of the litter interception study are illustrated in Figure 3.5 and summarised in Table 3.5.
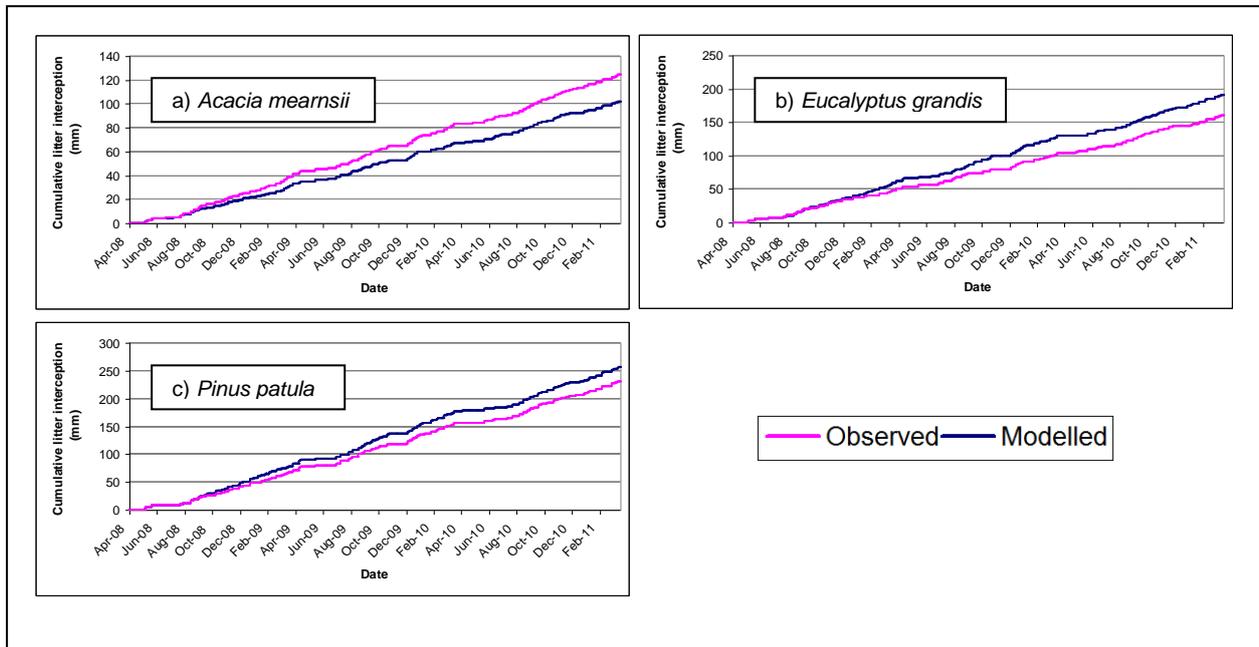
Figure 3.5   Cumulative observed and modelled litter interception simulated using idealised drying curves for three species at Two Streams.

This study shows that litter interception has an important role in the forest hydrological cycle, with as much as 13.4% of gross precipitation being intercepted by the 16 year old *P. patula* litter. The results of the cumulative modelled and observed litter interception are illustrated in Figure 3.5. The model results were good, with the actual difference between modelled and observed for *E. grandis*, *A. mearnsii* and *P. patula* being 1.6%, 1.2% and 1.3% respectively. This corresponds with a relative error of 18.8%, 18.2% and 10.7% respectively. From the summarized results in Table 3.5, it can be seen that *A. mearnsii* has the lowest litter interception with between 5.4% and 6.6% of gross precipitation being intercepted. *E. grandis* and *P. patula* had the highest modelled and observed litter interception with the modelled results being 10.1% and 13.4% respectively.

Table 3.5   Summary of observed and modelled litter interception results from April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed litter interception (mm)	Observed litter interception (%)	Modelled litter interception (mm)	Modelled litter interception (%)	Relative Error (%)
Eucalyptus	1884.7	160.4	8.5	191.1	10.1	18.8
Acacia	1884.7	124.7	6.6	102.1	5.4	18.2
Pinus	1909.7	231.2	12.1	255.9	13.4	10.7

Relative to the depth of litter (*cf.* Table 3.2), *E. grandis* has a high litter interception value. This may be due to the shape of the leaves that form the litter layer. The broad leaves act as "cups" that catch the throughfall, and provide very little resistance to the evaporative process. The simple litter interception model based on idealised drying curves is dependent upon the accuracy of the canopy interception model as the modelled throughfall is used as the model input. If the throughfall or canopy interception is modelled poorly, then the input into the litter interception model will induce a systematic error from the beginning of the simulation.

The statistics describing the performance of the litter interception model derived from the drying curves in comparison with the observed data measured at Two Streams for the period April 2008 to March 2011 is summarised in Table 3.6.

Table 3.6   Summary of litter interception model and observed litter interception statistics for the period April 2008 to March 2011.

Statistic	*Eucalyptus grandis*		*Acacia mearnsii*		*Pinus patula*	
	modelled	observed	modelled	observed	modelled	observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	0.18	0.15	0.10	0.12	0.24	0.21
Standard Error (mm)	0.016	0.014	0.01	0.01	0.023	0.021
Standard Deviation (mm)	0.51	0.46	0.28	0.33	0.74	0.68
Sample Variance (mm)	0.26	0.21	0.08	0.11	0.54	0.46
RMSE	0.24		0.10		0.23	
R^2	0.77		0.85		0.83	

From Table 3.6 it can be seen that mean, standard error, standard deviation and sample variance for the modelled and observed litter interception results are similar, indicating that the model performed well. This is also seen by the RMSE values for *E. grandis, A. mearnsii* and *P. patula* being between 0.1 and 0.24. The R^2 values are also very good with *A. mearnsii* having the highest at 0.85 and *E. grandis* the lowest at 0.77. To determine how the two models performed together, the cumulative water that drains to the soil was also considered.

6.3 Water that Drains to the Soil

The observed results for the water that drains to the soil, i.e. the "useable water", are a good indicator of how the canopy and litter interception models performed together as a whole/system. This is because the measured water that drains to the soil is measured as a separate entity and is not dependant on measured throughfall to calculate, as is the case with litter interception. Therefore, if the canopy and litter models did not perform well, then the modelled water that drained to the soil would not correspond well to the observed results, as the litter model depends on the modelled throughfall as an input. The comparative results of the cumulative modelled and observed water that drains to the soil is illustrated in Figure 3.6.
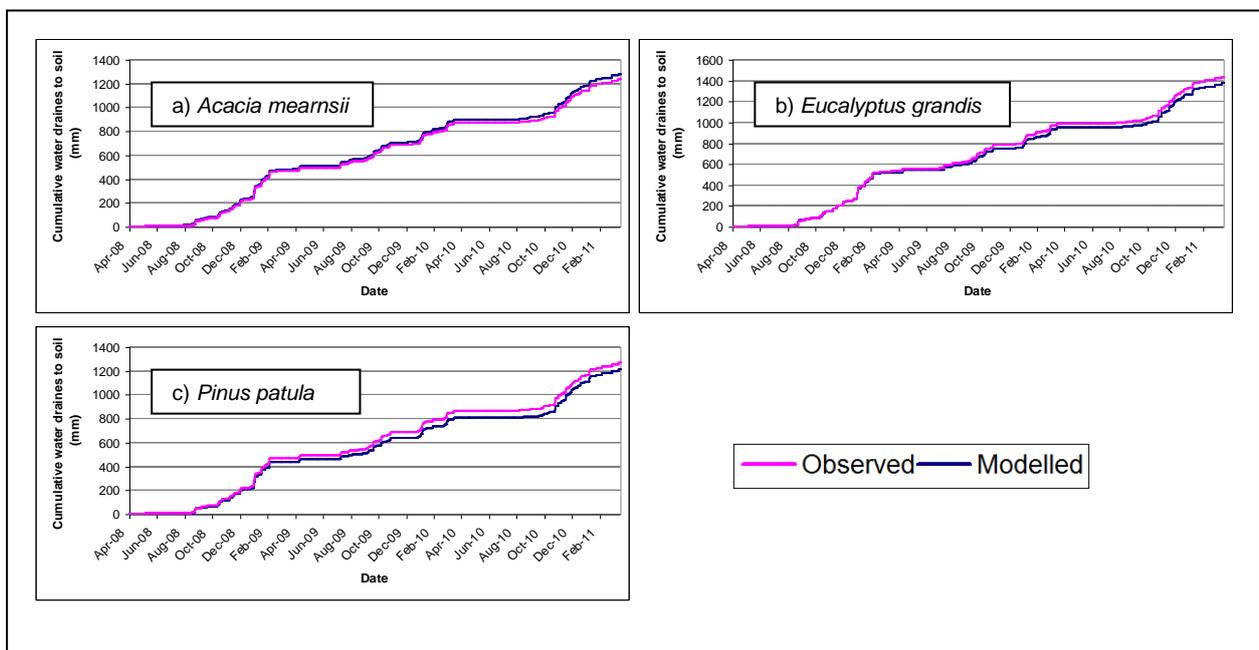
Figure 3.6   Cumulative observed and modelled water that drains to soil from April 2008 to March 2011 for three species at Two Streams.

Figure 3.6 shows that the modelled and observed results compare well, illustrating that the combination of the relatively complex canopy interception model and simple litter interception model work well together. The results are summarized in Table 3.7.

Table 3.7   Summary of observed and modelled water that drained to soil for April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed water drained to soil (mm)	Observed water drained to soil (%)	Modelled water drained to soil (mm)	Modelled water drained to soil (%)	Relative Error (%)
Eucalyptus	1884.7	1437.0	76.2	1375.2	72.9	4.3
Acacia	1884.7	1237.7	65.7	1281.5	64.3	2.1
Pinus	1909.7	1269.8	66.5	1209.7	63.3	4.8

From Table 3.7, it can be seen that the modelled water that drains to the soil is 3.3%, 1.4% and 3.2% higher than the observed results for *E. grandis, A. mearnsii* and *P. patula* respectively, with between 63.3% and 72.9% of gross precipitation reaching the soil. This corresponds to a relative error of 4.3%, 2.1% and 4.8% for *E. grandis, A. mearnsii* and *P. patula* respectively as shown in Table 3.7.

The statistics of the performance of the model derived from the drying curves to estimate the water that drains to the soil in comparison with the observed data measured at Two Streams for the period April 2008 to March 2011 are summarised in Table 3.8.

Table 3.8   Summary of modelled and observed water that drains to the soil statistics for the period April 2008 to March 2011.

Statistic	*Eucalyptus grandis*		*Acacia mearnsii*		*Pinus patula*	
	modelled	observed	modelled	observed	modelled	observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	1.29	1.35	1.20	1.16	1.13	1.20
Standard Error (mm)	0.134	0.141	0.131	0.123	0.128	0.132
Standard Deviation (mm)	4.36	4.44	4.10	4.01	4.13	4.20
Sample Variance (mm)	19.05	19.14	16.80	16.33	17.10	17.60
RMSE	0.33		0.27		0.55	
R^2	0.83		0.85		0.81	

From Table 3.8 it can be seen that the combination of the "variable storage Gash model" and the litter interception model derived from drying curves worked well, as the descriptive statistics for the modelled and observed water that drains to the soil are very similar. This is also seen by the high R^2 values for *E. grandis*, *A. mearnsii*, and *P. patula* of 0.83, 0.85 and 0.81 respectively.

Based on the results obtained, it is accepted that the model is representative of the processes and on this basis the modelling study was extended to a longer period. The same model variables used to model for the study period between April 2008 to March 2011 was assumed for the extended period

from September 1998 to March 2011. The results of the data modelled for the period from September 1998 to March 2011 are summarized in Table 3.9.

Table 3.9   Summary of all results modelled from September 1998 to March 2011.

Genus	Gross Precipitation (mm)	Modelled canopy interception (mm)	Modelled canopy interception (%)	Modelled litter interception (mm)	Modelled litter interception (%)	Modelled water drained to soil (mm)	Modelled water drained to soil (%)
Eucalyptus	11145.5	1805.6	16.2	869.3	7.8	8470.6	76.0
Acacia	11145.5	3020.4	27.1	702.2	6.3	7422.9	66.6
Pinus	11145.5	2708.4	24.3	1605.0	14.4	6832.2	61.3

The modelled results for the study period between April 2008 and March 2011 are similar to those obtained from modelling between September 1998 and March 2011. The difference in the results of the modelled water that drains to the soil for the two periods are 3.1%, 2.3% and 2.0% for *E. grandis*, *A. mearnsii* and *P. patula* respectively. This once again highlights that the climatic conditions during the study period are typical of the catchment as the difference in canopy and litter interception as well as water that drains to soil are very similar.

7. CONCLUSION

This study confirms that interception plays a very important role in the forest hydrological cycle, with between 63.3% and 72.9% of gross precipitation being available water that drains to the soil, after the losses due to canopy and litter interception. This also highlights the importance of including and accurately representing canopy and litter interception in water resources planning models. Both the "variable storage Gash model" and litter interception models performed well. The "variable storage Gash model" is conceptually complex, but can be applied with readily available data. Although the input data requirements are fewer than the original model, an added consideration of the change in canopy storage capacity depending on the rainfall intensity has been added and is an important conceptual advance. This addition along with the consideration for the canopy water retention characteristics have resulted in the canopy interception simulations being very good. This point was highlighted by considering that *E. grandis* had the highest LAI, but had the lowest canopy interception due to is low water retention because of the angle at which the large leaves hang, as well as their smooth, waxy surface. Conversely, the *A. mearnsii* had the second largest LAI, but the largest canopy interception due to the high water retention characteristics of its small pinnately compound leaves. While the "variable storage Gash model" may be considered complex, the litter interception model which is based on idealised drying curves is very simple. However, although the model may be simple, it performed well. This can be explained by the fact that unlike canopy interception which is strongly influenced by many factors such as storage capacity, potential evaporation, rainfall intensity, rainfall duration amongst others, litter interception is mostly dependant on storage capacity and modelling it is dependent on the accurate estimation thereof. This is because the evaporative drivers under the canopy such as wind, temperature and radiation are moderated relative to those above canopy. Therefore, as long as the inputs of simulated throughfall from the "variable storage Gash model" are adequate and the litter storage capacity is estimated accurately, the model should perform well. It could in fact be argued that the "variable storage Gash model" and litter interception models should not be considered as separated models, but as one model that simulates "total interception" (i.e. canopy + litter interception). Therefore, a model should aim for a requisite simplicity by discarding some detail but maintains conceptual clarity and scientific rigour (Stirzaker *et al.*, 2010).

The canopy interception model described here could be applied for national scale studies as it is not site specific. However, although the litter interception model performed well, it cannot be transferred and used elsewhere as the data was site, species and age dependant. However, litter samples can easily be obtained and dried and further studies to generate national litter interception characteristics are a logical way forward. However, the CSIR Two Streams research catchment where the models were developed was situated in a mist belt area, so the high canopy interception results could be attributed to this fact, as over 50% of the daily rainfall events were less than 1 mm. Therefore, further research in other climatic areas, with different rainfall characteristics is required.

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CHAPTER 4

National Estimates of Canopy Interception using the Variable Storage Gash
Analytical Interception Model in South Africa

National estimates of canopy interception using the Variable Storage Gash analytical interception model in South Africa

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ABSTRACT

The problem of modelling canopy interception at a catchment scale has received remarkably little attention, with even fewer studies at the national scale. Canopy interception for the three most common commercial forestry genera in South Africa (including Lesotho and Swaziland) *viz., Eucalyptus, Acacia* and *Pinus* was modelled using the "variable storage Gash model" together with data from a national database of climatic parameters available at the quinary catchment scale for all catchments with a mean annual precipitation exceeding 600 mm. The results of the study show that spatially, canopy interception is highly variable depending on the genus, rainfall intensity and rainfall seasonality. Canopy interception in South Africa was shown to range between less than 10% and up to 40% of gross precipitation, or between 100 and 300 mm.year^{-1}.

Keywords: Canopy interception, Gash model, quinary catchment, South Africa

1.   INTRODUCTION

Canopy rainfall interception plays an important role in the water balance of a forested catchment (Anzhi *et al*., 2005). There is evidence in the available literature that interception can be as high as 10 to 55% of the gross precipitation (McNaughton and Jarvis, 1983; Calder, 1990) and therefore an important consideration in water resources planning. The processes of canopy interception are complex and difficult to quantify and consequently much of our understanding originates from very intensive research studies undertaken at a single site. Modelling canopy interception at a catchment scale has received remarkably little attention (Dye and Versfeld, 1992) and even less at a national scale. However, given the very high estimates of canopy interception by some authors, and the significance attached to the water use of commercial forestry plantations in South Africa (Jewitt, 2002;

Dye and Versfeld, 2000), it is important to assess the potential impact of canopy interception on both catchment and national scale water resources. In order to achieve this requires a model that is not parameter intensive, that makes use of parameters that are easily attainable, but retains the conceptual clarity and scientific rigour necessary to ensure confidence in the model output (Stirzaker *et al.*, 2010).

There have been many models developed to predict canopy interception according to the characteristics of the rainfall and canopy. These models can be grouped into three categories:

1. Empirical or Mathematical models (e.g. Horton, 1919; Merriam, 1960; Aston, 1979; Massman, 1980; von Hoyningen-Huene, 1981).
2. Stochastic Models (e.g. Calder, 1986; Hall, 2003).
3. Physical and related models (e.g. Rutter *et al.*, 1971, 1975; Rutter and Morton, 1977; Gash, 1979; Gash *et al.*, 1995).[1]

The Gash (1979) and Gash *et al.* (1995) models are probably the best known and most commonly applied canopy interception models. Essentially, these account for forest canopy, canopy structure, tree density and different climatic conditions and are modifications to the Rutter models introduced by Gash (1979) and Gash *et al.* (1995). These models do require considerable input of climatic data and vegetation-structure parameters (Aboal *et al.*, 1999) limiting, until now, their applicability at a national scale. In this paper, we aim to assess the significance of canopy interception from commercial afforestation across South Africa. This is achieved by applying the "variable storage Gash model"[1] (*cf.* Chapter 3) to estimate potential canopy interception for all quinary catchments[2] (Q_nC) in South Africa with a mean annual precipitation exceeding 600 mm as these are assumed to cover all catchments where commercial forestry plantations could exist across South Africa. The climatic parameters required include gross precipitation, evaporation, and rainfall rate. As described in Chapter 3, the canopy structure parameters are described using LAI and elemental volume as inputs to parameterise the model.

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[1] The reader is referred to Chapter 3 for a more detailed description of the "variable storage Gash model".
[2] Quinary catchments are 5th level sub-basins derived by Schulze and Horan (2009) and are commonly used in water resources studies in South Africa.

2. METHODOLOGY

To model canopy interception for the whole of South Africa (including Lesotho and Swaziland), the "variable storage Gash model" was used (*cf*. Chapter 3) for all Q_nC's in South Africa with a mean annual precipitation greater than 600 mm, as these are considered viable for commercial forestry. Schulze and Horan (2009) derived the quinary catchments (5th level sub-basin) by subdividing each of the 1946 quaternary catchments (4th level sub-basin) into three sub-catchments using Jenks optimisation, together with the 200 m digital elevation model available for southern Africa. Climatic data from a national database was used for modelling canopy interception at the Q_nC scale (Schulze *et al*., 2009). The database includes 50 years (1950-1999) of daily rainfall, maximum and minimum temperature, solar radiation and Penman-Monteith reference evaporation for each Q_nC, which is widely used in other water resources studies in South Africa.

2.1 Climatic Parameters

The climatic parameters required are gross precipitation (P_g), mean rainfall rate (R) and mean evaporation rate (E). In this study, gross precipitation and Penman-Monteith reference evaporation estimates from the quinary catchment database (Schulze *et al*., 2009) were used for the fifty year period.

2.1.1 Precipitation

The rainfall station selected to represent the parent quaternary catchment was also selected to represent all three quinary catchments (located within the quaternary). Due to a lack of reliable station data in certain areas, a particular rainfall station could "drive" the hydrology of more than one quaternary catchment (and hence quinary catchment). In total, 1240 national rainfall "driver" stations were selected to generate daily rainfall for each of the 5838 quinaries. Multiplicative rainfall adjustment factors, determined for each Q_nC, were applied to the selected driver station's daily record in order to generate rainfall data that was deemed more representative of that Q_nC (Schulze *et al*., 2009).

2.1.2 Reference evaporation by the Penman-Monteith Method

The reference evaporation derived by the Penman Monteith FAO 56 method described in Schulze *et al*., (2007) was used in modelling the canopy interception. The reference evaporation in the Q_nC database is calculated from inputs of daily maximum and minimum temperatures described in Section 2.1.3 over South Africa on a 1' x 1' (~ 1.7 x 1.7 km) raster grid for 50 years, based on research by Schulze and Maharaj (2004).

2.1.3 Temperature

Schulze and Maharaj (2004) developed a comprehensive temperature database for southern Africa. A 50 year (1950 to 1999) record of daily maximum and minimum temperature was generated for each of the 437 039 grid cells (1' by 1') covering southern Africa. This was achieved by selecting two independent (located in different quadrants) stations from a total of 973 stations containing observed, patched and quality controlled daily record. Regional lapse rates were used to adjust for differences between the altitude of the two selected stations and the mean altitude of each grid cell.

Schulze *et al*., (2009) selected a representative temperature "station" for each Q_nC as follows. The 200 m digital elevation model was used to calculate the spatially averaged altitude for each Q_nC. Grid cells with mean altitudes similar to those of the Q_nC means, and located as close as possible to the Q_nC centroid (and preferably located within the quinary boundary), were then selected to represent each of the 5838 Q_nC's.

2.1.4 Mean rainfall rate

Mean rainfall rate (*R*) data for South Africa are not available in the Q_nC database. In order to derive these, the rainfall rate was estimated by calculating and applying a seasonal average rainfall intensity correction factor which is described next.

Schulze (1980) provided a distribution of kinetic energy of rainfall based on data from fourteen rainfall stations across South Africa. Since kinetic energy of rainfall and rainfall intensity are directly related (van Dijk *et al*., 2002), kinetic energy was used as a surrogate to determine the relative rainfall intensity for the seasonal rainfall regions in South Africa derived and mapped by Schulze and Maharaj (2007). The average rainfall of an area may be high or low, have a high or relatively low variability of rainfall from one year to the next or its rainfall may be concentrated over a short rainy season or spread over a longer period (Schulze and Maharaj, 2007). As a result of rainfall seasonality and

concentration, the rainfall intensity for these different areas is also affected. Some areas may have high intensity, short duration thunderstorms, while others, such as the Western Cape, are dominated by low intensity winter frontal rainfall of a longer duration. Hence, the canopy interception will vary accordingly. Rainfall seasonality is also an important hydrological consideration when considering canopy interception.

In this study, data from the 14 weather stations used by Schulze (1980) were first grouped into summer and winter "envelopes", where the maximum and minimum mean kinetic energy for these "envelopes" was determined. This was achieved using 100 mm of rainfall as a reference value as illustrated by the example in Figure 4.1 for Johannesburg (summer rainfall region) and Cape Town (winter rainfall region). Next, these stations were overlayed onto a rainfall seasonality map of South Africa as shown in Figure 4.2 (Schulze and Maharaj, 2007). Depending on the location of the weather station, a rainfall season was assigned to each station (Table 4.1).
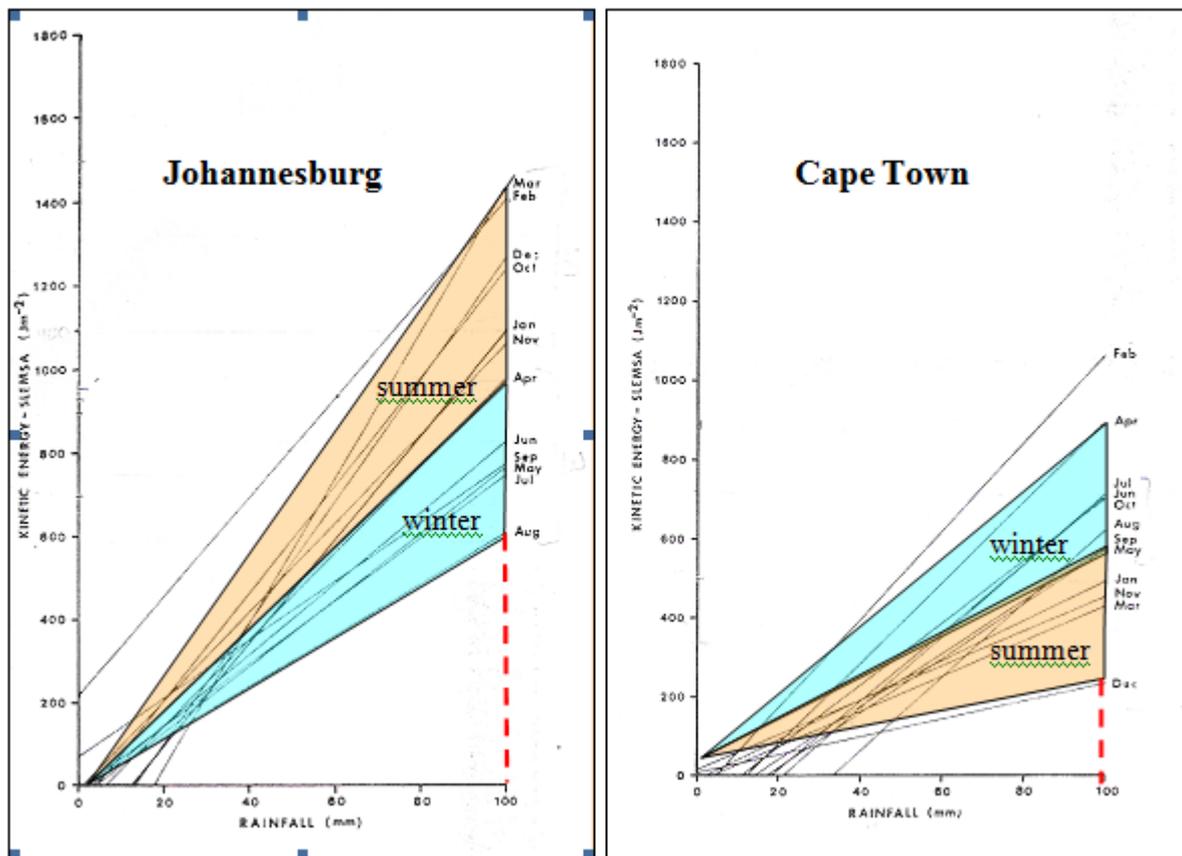
Figure 4.1   Monthly kinetic energy: rainfall relationship (after Schulze, 1980).

Table 4.1   Kinetic energy from Schulze (1980) using 100 mm of rainfall as a reference.

Town	Seasonality	Summer			Winter		
		Max (J.m^{-2})	Min (J.m^{-2})	Mean (J.m^{-2})	Max (J.m^{-2})	Min (J.m^{-2})	Mean (J.m^{-2})
Beaufort West	Very Late Summer	1600	*1100*	1350	700	200	450
Bloemfontein	Late Summer	1200	900	1050	600	300	450
Cape Town	Winter	500	300	400	900	600	750
Cathedral Peak	Mid Summer	1200	800	1000	700	300	500
Cedara	Mid Summer	1200	1000	1100	700	100	400
Durban	Mid Summer	1200	1050	1125	800	600	700
East London	All Year	1000	550	775	1400	1100	1250
Grootfontein	Very Late Summer	1400	800	1100	650	200	425
Johannesburg	Mid Summer	1400	1100	1250	950	600	775
Kimberly	Late Summer	1350	1000	1175	750	400	575
Pietersburg	Early/Mid Summer	1500	1150	1325	1050	500	775
Port Elizabeth	Early Summer	1000	770	885	750	500	625
Pretoria	Early Summer	1500	1100	1300	700	200	450
Upington	Very Late Summer	1400	1100	1250	900	300	600

Schulze and Maharaj (2007) derived the rainfall seasonality using rainfall concentration determined from the Markham (1970) technique, at a Q_nC scale. In this study, this methodology was applied to the QC database to determine an updated rainfall seasonality map using mean monthly rainfall (Schulze and Kunz, 2010). The rainfall seasonality categories are the same as those used by Schulze and Maharaj (2007).
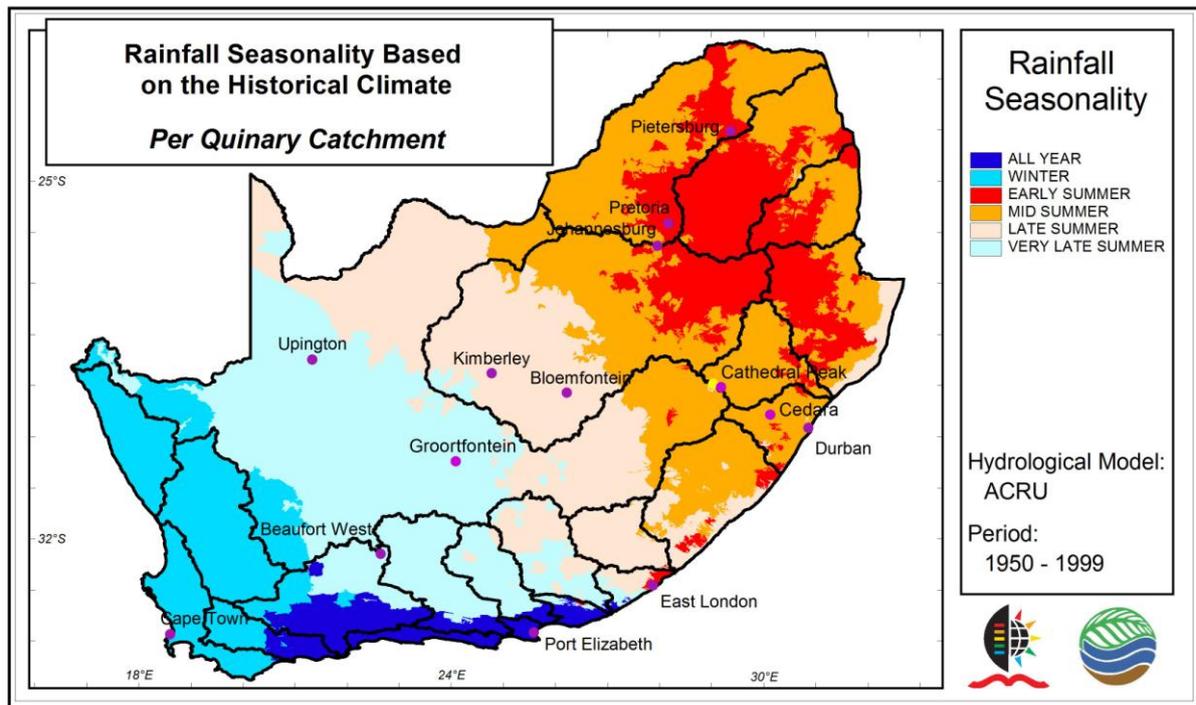
Figure 4.2   Rainfall seasonality per quinary catchment (Schulze and Kunz, 2010) and weather stations used by Schulze (1980).

The daily rainfall cannot be multiplied by a value less than 1, as this would result in a rainfall intensity lower than the daily rainfall. Therefore, to normalize the data in Table 4.1, the lowest mean kinetic energy for summer and winter was used to divide the rest of the data, so that the lowest mean value was 1 as shown in Table 4.2.

Table 4.2   Normalized data for each of the 14 weather stations.

Town	Seasonality	Summer			Winter		
		Max (J.m^{-2})	Min (J.m^{-2})	Mean (J.m^{-2})	Max (J.m^{-2})	Min (J.m^{-2})	Mean (J.m^{-2})
Beaufort West	Very Late Summer	4.00	2.75	3.38	1.75	0.50	1.13
Bloemfontein	Late Summer	3.00	2.25	2.63	1.50	0.75	1.13
Cape Town	Winter	1.25	0.75	1.00	2.25	1.50	1.88
Cathedral Peak	Mid Summer	3.00	2.00	2.50	1.75	0.75	1.25
Cedara	Mid Summer	3.00	2.50	2.75	1.75	0.25	1.00
Durban	Mid Summer	3.00	2.63	2.81	2.00	1.50	1.75
East London	All Year	2.50	1.38	1.94	3.50	2.75	3.13
Grootfontein	Very Late Summer	3.50	2.00	2.75	1.63	0.50	1.06
Johannesburg	Mid Summer	3.50	2.75	3.13	2.38	1.50	1.94

Kimberly	Late Summer	3.38	2.50	2.94	1.88	1.00	1.44
Pietersburg	Early/Mid Summer	3.75	2.88	3.31	2.63	1.25	1.94
Port Elizabeth	Early Summer	2.50	1.93	2.21	1.88	1.25	1.56
Pretoria	Early Summer	3.75	2.75	3.25	1.75	0.50	1.13
Upington	Very Late Summer	3.50	2.75	3.13	2.25	0.75	1.50

The normalized correction factors established in Table 4.2 were then averaged for each of the six rainfall seasonality regions as derived by Schulze and Maharaj (2007) to obtain rainfall intensity correction factors as shown in Table 4.3.

Table 4.3   Rainfall rate correction factors per rainfall seasonality zone derived from the data of Schulze (1980).

Season	Summer	Winter
All Year	1.94	3.13
Winter	1.00	1.88
Early Summer	2.86	1.54
Mid Summer	2.68	1.33
Late Summer	2.79	1.29
Very Late Summer	3.09	1.23

2.2   Canopy Structure Parameters

The canopy structure parameters in the "variable storage Gash model" are described using LAI and elemental volume as the primary inputs.

2.2.1   Leaf area index

The leaf area indices (LAI) used by Gush *et al*., (2001) which were extracted from Summerton (1995) for each of the three most common commercial forestry genera in South Africa, namely *Pinus*, *Eucalyptus* and *Acacia* were assigned to each Q_nC. Based on the assumptions of Gush *et al*., (2001), the Q_nC's with an MAP of greater than 600 mm were selected as suitable for commercial forestry (3087 in total) as shown in Figure 4.3. Those catchments with an MAP below 600 mm are considered economically unviable for commercial afforestation and therefore excluded. The selected Q_nC's were then assigned to one of four South African forestry climatic zones identified by Summerton (1995),

namely Mpumalanga, KwaZulu-Natal, Eastern Cape and Zululand. The climatic zones were delineated according to climatic homogeneity and not necessarily according to provincial boundaries. For example,, Q_nC's in the Highveld, Eastern Free State, Lesotho as well as in the Western and Southern Cape were assigned to the "Eastern Cape" zone, that zone being deemed most similar climatically (Gush *et al*., 2001).
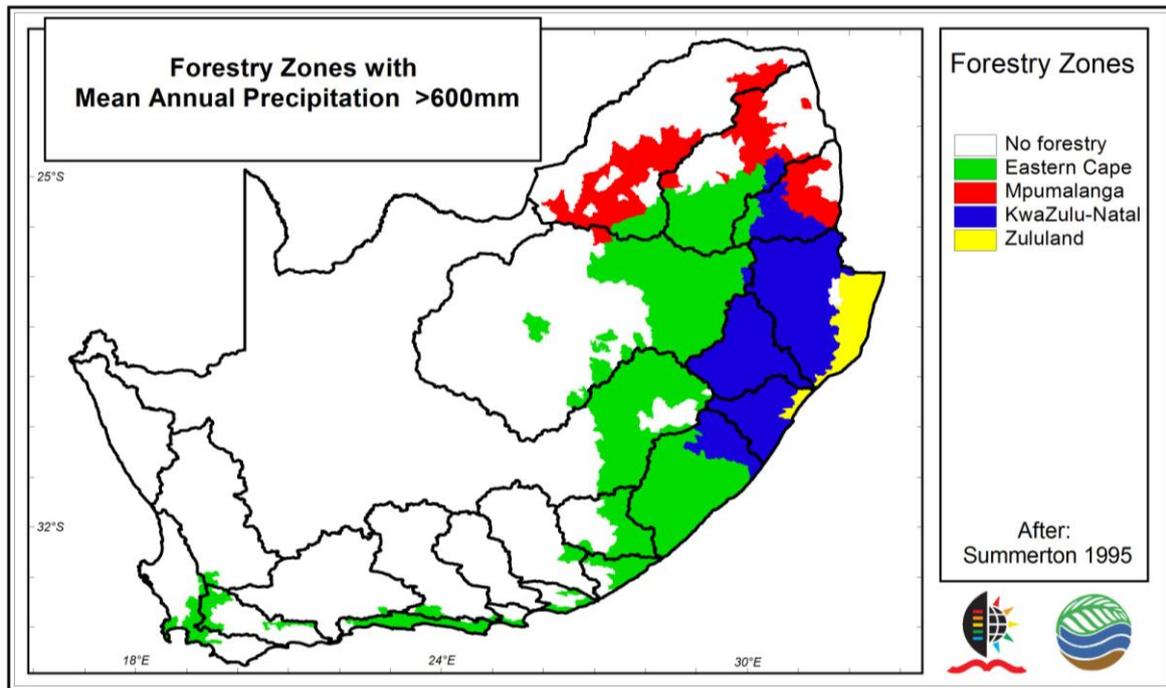
Figure 4.3   The distribution of the four forestry climatic zones for quinary catchments with an MAP exceeding 600 mm/annum (after Summerton, 1995).

For each of the three commercial forestry genera, a representative age was assigned by Gush *et al*., (2001) based on analyses of the mean and median water use within a catchment with a normalised age distribution. The motivation of Gush *et al*., (2001) to determine a representative age of each tree genus was to establish an average streamflow reduction over a typical rotation. The ages for each genus are as follows; 4 year old *Eucalyptus*, 7 year old *Pinus*, and 4 year old *Acacia mearnsii* (Gush *et al.*, 2001). These ages are assumed to represent the median condition of all plantations in an area and are accepted in South African water resources planning. The leaf area indices assigned to each genus for the four forestry climatic zones based on the above mentioned ages are summarized in Table 4.4:

Table 4.4   Leaf area index values for the three common commercial forestry genera for representative ages derived by Gush *et al.,* (2001) for the four forestry zones suggested by Summerton (1995)

Variable	LAI		
Zone / Genus	*Eucalyptus*	*Acacia*	*Pinus*
Mpumalanga	3.5	2.5	3.5
KwaZulu-Natal	4.2	2.8	3.8
Eastern Cape	2.7	3.0	3.1
Zululand	4.4	2.8	3.8

2.2.2. Canopy cover fraction

Gash *et al*., (1995) introduced the canopy cover fraction (*c*) to the Gash (1979) model to account for inadequacies in modelling sparse canopies. Van Dijk and Bruijnzeel (2001a; 2001b) then modified the Gash *et al*. (1995) model allowing it to be applied to rapidly growing vegetation where the LAI is changing through time. For the "variable storage Gash model", LAI is defined as the cumulative one-sided area of leaves per unit area. LAI and *c*, can be related to one another via the Beer-Lambert equation which describes the attenuation of radiation (i.e. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate far through leaves, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between *c* and LAI is thus given by Equation 4.1 and is illustrated in Figure 4.4, where the extinction coefficient *k* = 0.5 (Landsberg and Waring, 1997; Battaglia *et al*., 2004) was used in the "variable storage Gash model".

$$c = 1 - e^{-k.\text{LAI}} \tag{4.1}$$
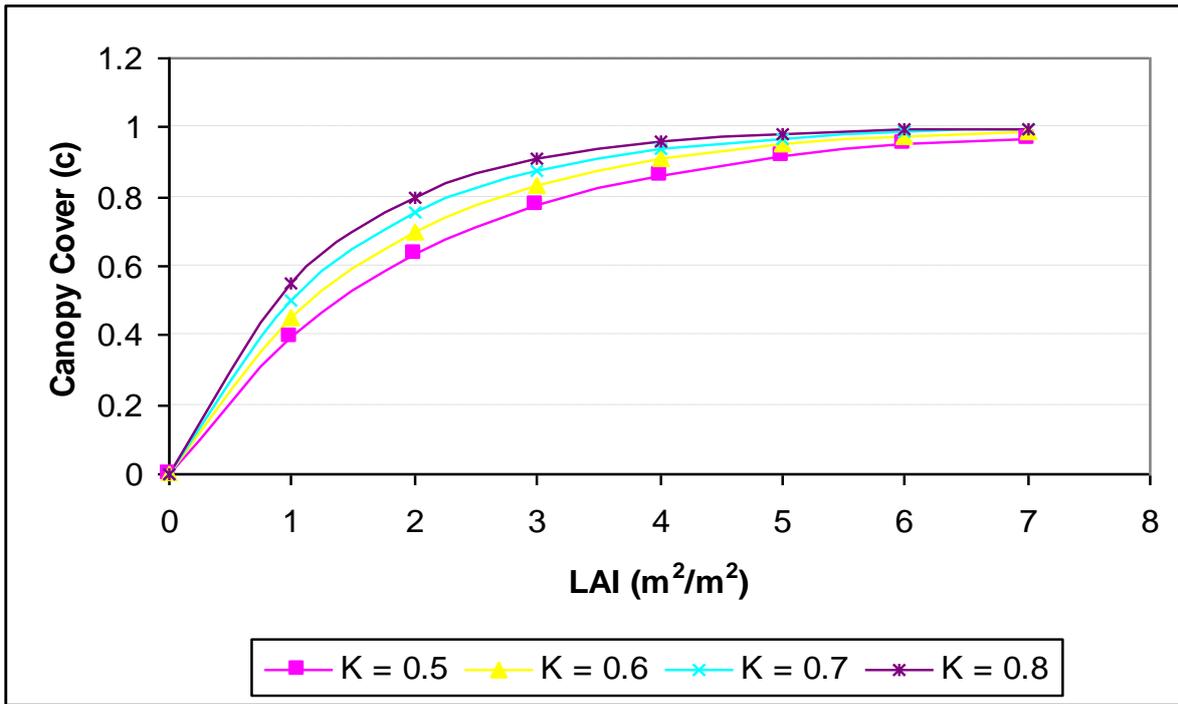
Figure 4.4   Beer-Lambert canopy cover curves for different extinction coefficients (K).

The free throughfall coefficient (p) is the fraction of rain that passes through a canopy during a storm without touching the canopy and can be described as $p = 1\text{-}c$ (van Dijk and Bruijnzeel, 2001a).

2.2.3   Storage capacity

Particular attention needs to be devoted to the accurate estimation of the storage capacity of the canopy, as it is reported to be a critical parameter in interception models (Aboal *et al.*, 1999; Llorens and Gallart, 2000). An often ignored factor when modelling or measuring canopy interception which has been incorporated into the "variable storage Gash model" is that of drop size and intensity. The importance of drop size and intensity when determining canopy interception losses was first established through experimental work in the tropical climates of Indonesia and India by Calder (1986). Calder (1986) developed a stochastic interception model that predicts that for storms with the same total rainfall, interception losses would be larger for those with smaller drop sizes. The model also considers the drop retention by the canopy, and is partially dependent on the kinetic energy and hence drop size. The ability of a canopy to retain rain drops is parameterised in the model by q, the drop retention number. The drop retention is dependent upon the size and kinetic energy of the impacting drop, as well as canopy properties such as 'wettability' and leaf angle (Hall, 2003).

To incorporate the dependence of q on both drop volume and therefore kinetic energy into the model, a vegetation/species specific parameter is introduced, termed the maximum elemental volume (v_e^{max})

and is expressed in Equation 4.2. This is calculated by considering drops impacting the surface with a kinetic energy as close to zero as possible, which according to Calder (1996) are events with an intensity of less than 0.36 mm.h^{-1}. The v_e^{max} values used in this study are as follows:

- *Eucalyptus grandis* = 0.24
- *Acacia mearnsii* = 0.63
- *Pinus patula* = 0.51

$$v_e^{max} = q.v_0 \text{ (i.e. } q = \frac{v_e^{max}}{v_0}) \tag{4.2}$$

where:

q   -   drop retention

v_e^{max} -   is the maximum volume of water retained by a canopy element (mm^3), and

v_0 -   is the mean volume of the rain drop (mm^3) with almost zero kinetic energy.

The term maximum storage capacity (S_c^{max}) which is obtained when the canopy is wetted with drops of almost "zero" kinetic energy and is defined as:

$$S_c^{max} = v_e^{max}.\text{LAI} = q.v_0.\text{LAI} \tag{4.3}$$

The storage capacity (S_c) for non-zero kinetic energy drops can therefore is defined as:

$$S_c = v_e.\text{LAI} = q.v.\text{LAI} \tag{4.4}$$

The drop volume (v) is estimated using the Marshall-Palmer (1948) equation:

$$v = a.R^b \tag{4.5}$$

where parameters $a = 0.124$, $b = 0.63$, and

R   -   Rainfall rate or intensity (mm.h^{-1}).

In order to operate the model for a particular vegetation type requires values for two vegetation specific parameters S_c^{max} and v_e^{max}. A functional relationship between S_c/S_c^{max} (equations 4.6a and 4.6b) and v is also required. Calder (1996) developed the following empirical exponential relationship from rainfall simulator experiments:

$$S_c/S_c^{max} = 1 \qquad\qquad\qquad \text{for } v < 0.065 \tag{4.6a}$$
$$S_c/S_c^{max} = 0.5 + 0.73.\exp(-5.5.v) \qquad \text{for } v > 0.065 \tag{4.6b}$$

Then, rearranging the Marshall-Palmer (1948) equation to determine R for $v < 0.065$ it can be established that $S_c/S_c^{max} = 1$ for $R < 0.36$ mm.h^{-1}. From field measurements of leaf area index and

storage capacity for events with $R < 0.36$ mm.h^{-1}, the vegetation/species specific v_e^{max} can be calculated. By knowing the v from the Marshall-Palmer (1948) equation and S_c^{max}, the variable S_c can be calculated as the product of S_c/S_c^{max} and S_c^{max}.

The maximum elemental volume (v_e^{max}) does not change with the growth of the tree due to the linear relationship between S_c^{max} and LAI. The linear relationship between storage capacity and LAI for a given vegetation type of constant physiognomy and configuration has been corroborated by the results of Aston (1979), Von-Hoyningen-Huene (1981), Pitman (1989), Liu, (1998) and van Dijk and Bruijnzeel (2001).

3. RESULTS AND DISCUSSION

The results of this study are illustrated in Figures 4.5 to 4.13. Figures 4.5 to 4.7 illustrate the simulated mean annual canopy interception loss for the important *Eucalyptus, Acacia* and *Pinus* genera, which are the three most common commercial forestry genera in South Africa. Figures 4.8 to 4.10 illustrate the simulated mean annual canopy interception loss as a percentage of the mean annual precipitation for the corresponding Q$_n$Cs. Figures 4.11 to 4.13 illustrate the simulated mean canopy interception loss per rain day for each of the quinary catchments that contain forestry. This was calculated by dividing the mean annual canopy interception by the number of rain days per quinary catchment, as derived from the Q$_n$C rainfall database.
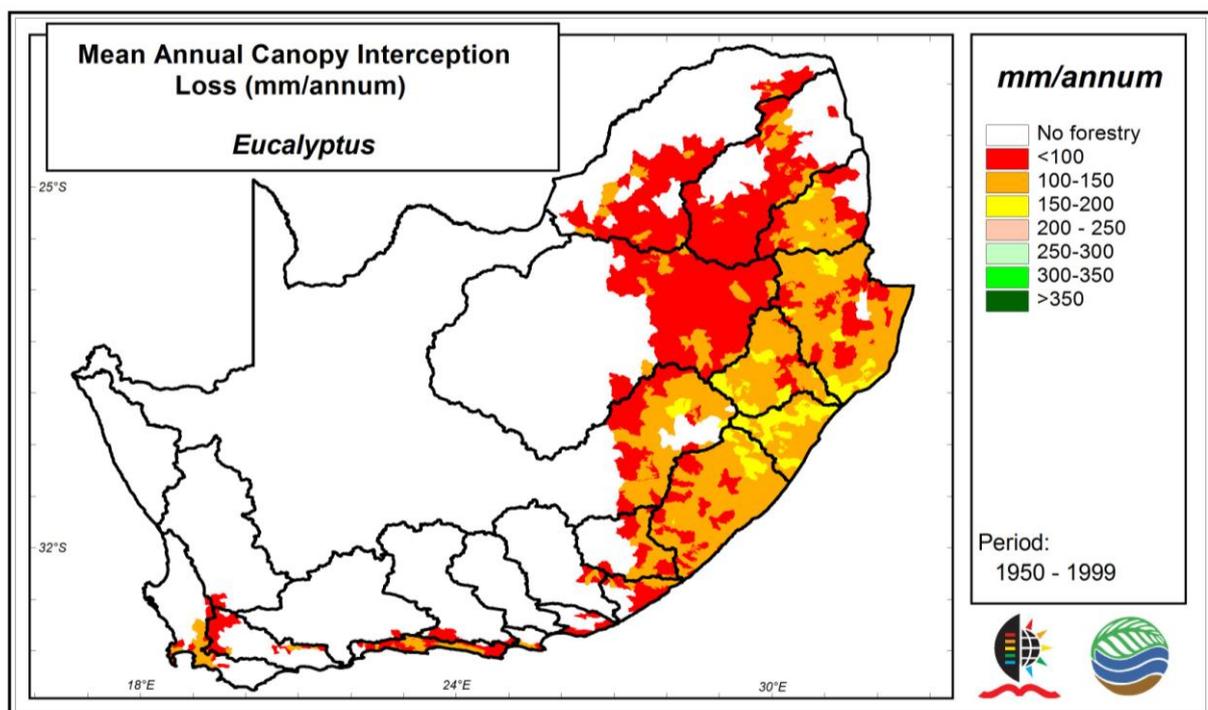
Figure 4.5   Representative mean annual canopy interception loss for *Eucalyptus* per quinary catchment in South Africa.
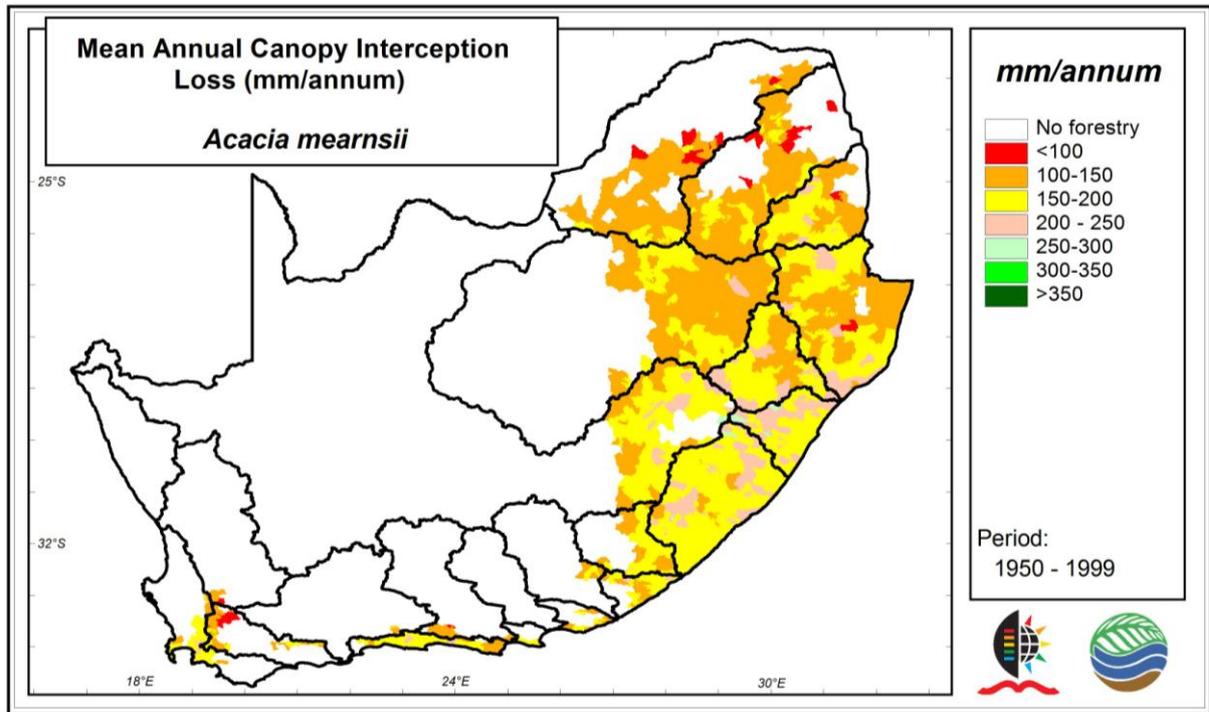
Figure 4.6   Representative mean annual canopy interception loss for *Acacia mearnsii* per quinary catchment in South Africa.
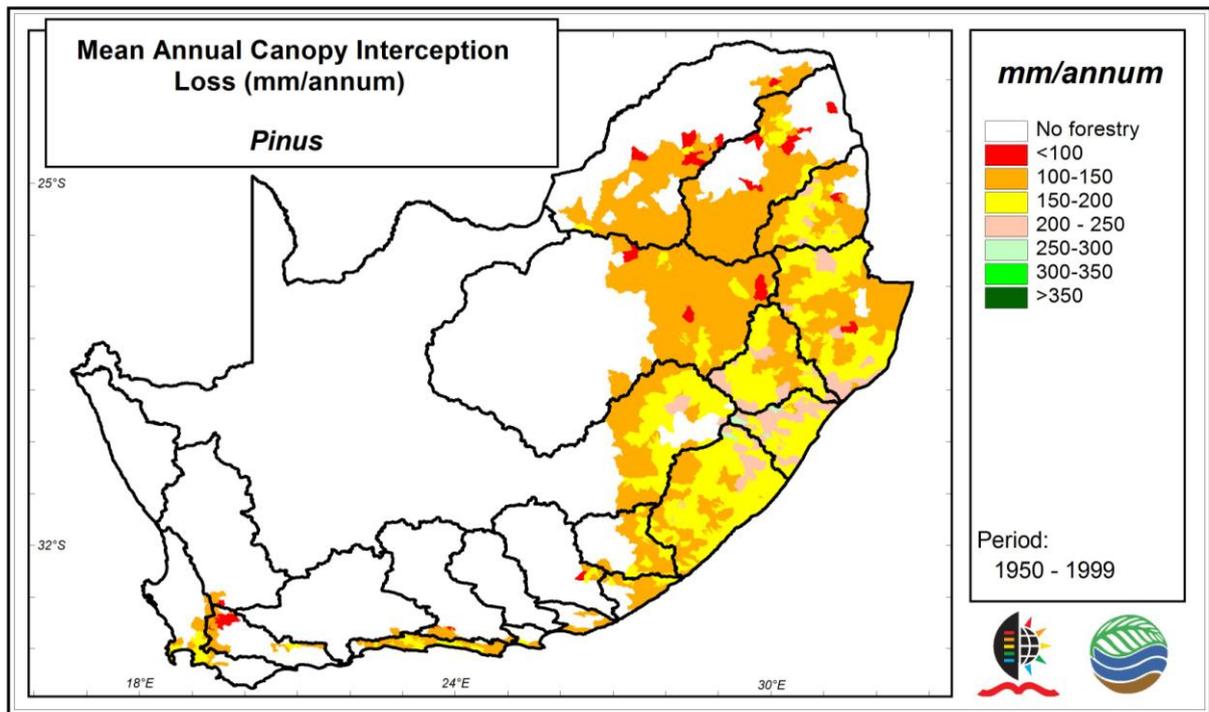
Figure 4.7   Representative mean annual canopy interception loss for *Pinus* per quinary catchment in South Africa.

From Figures 4.5 to 4.7, it can be seen that east of the Drakensberg escarpment (i.e. KwaZulu-Natal and Zululand forestry zones as identified by Summerton, (1995)) generally has the highest canopy interception. On the eastern side of the escarpment, the interception loss for *Eucalyptus* (Figure 4.5) is generally between 100 and 200 mm per year, with a few quinary catchments having an interception of less than 100 mm per year. West of the escarpment, the interception loss by *Eucalyptus* is lower than the eastern side with most quinary catchments having a canopy interception (loss) of less than 100 mm per year and no more than 150 mm per year. The southern and south Western Cape shows interception losses between 100 and 150 mm per year. *Acacia mearnsii* (Figure 4.6) shows slightly higher canopy interception than that of *Eucalyptus*. East of the escarpment shows interception losses between 100 and 250 mm per year, with a few quinary catchments having interception losses between 250 and 300 mm per year. Most areas west of the escarpment show interception losses of between 100 and 200 mm per year. Similarly, in the southern and south Western Cape (i.e. winter and all year rainfall regions) canopy interception by *Acacia mearnsii* is between 150 and 250 mm per year, with a few quinary catchments having less than 100 mm per year. The canopy interception of *Pinus* (Figure 4.7) on the east of the escarpment is between 100 and 250 mm per year, with two quinary catchments on the boundary between the Tugela and Umgeni primary catchments showing canopy interception of between 250 and 300 mm per year. In the southern and south Western Cape, interception by *Pinus* ranges from less than 100 mm per year to 200 mm of gross precipitation per year.
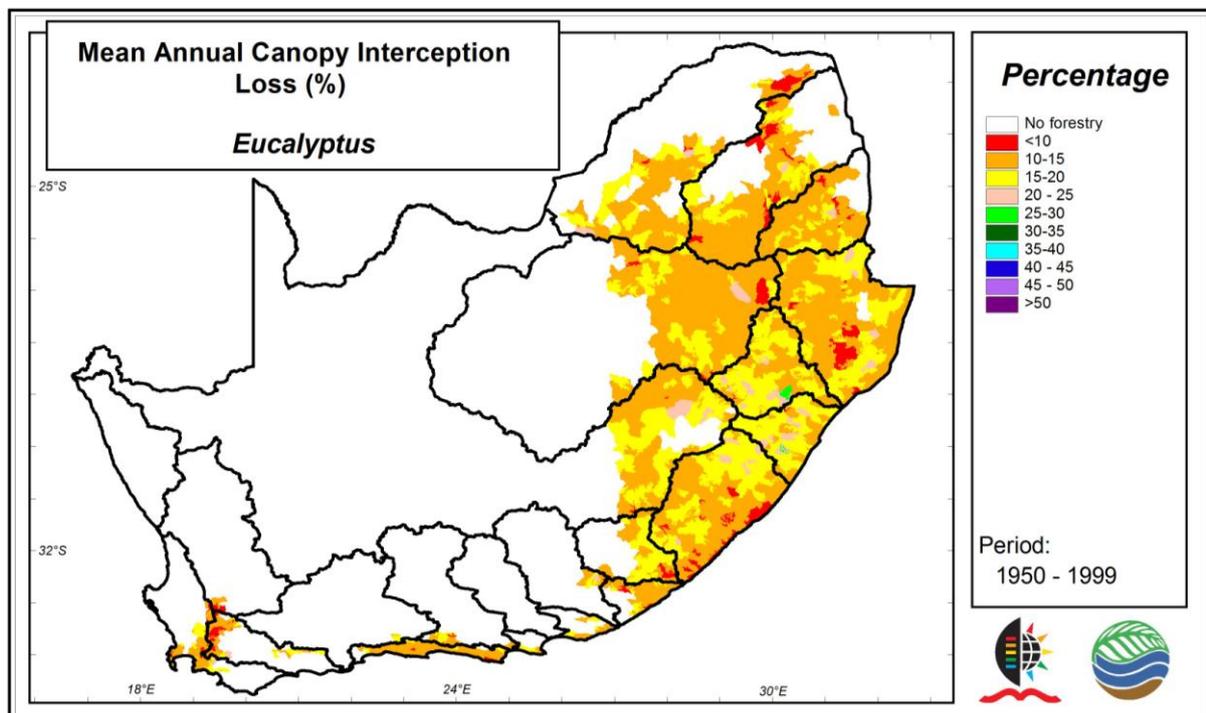
Figure 4.8   Representative mean annual canopy interception loss for *Eucalyptus* as a percentage of gross precipitation per quinary catchment for South Africa.
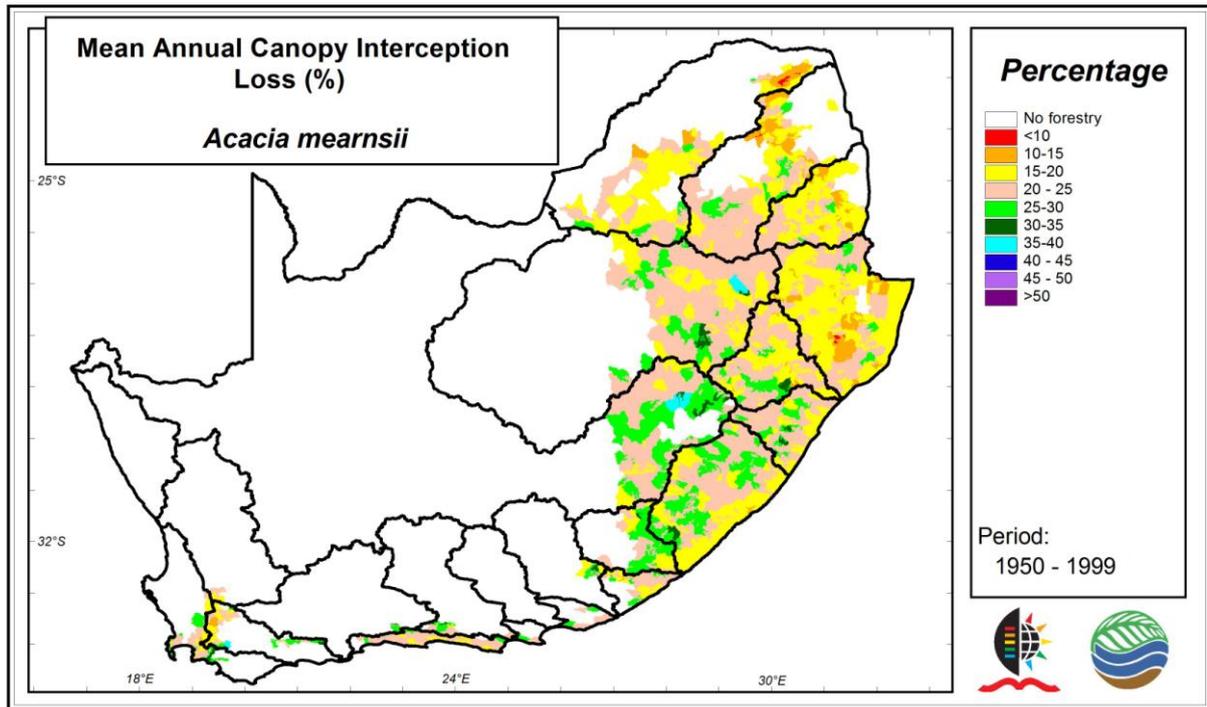
Figure 4.9   Representative mean annual canopy interception loss for *Acacia mearnsii* as a percentage of gross precipitation per quinary catchment for South Africa.
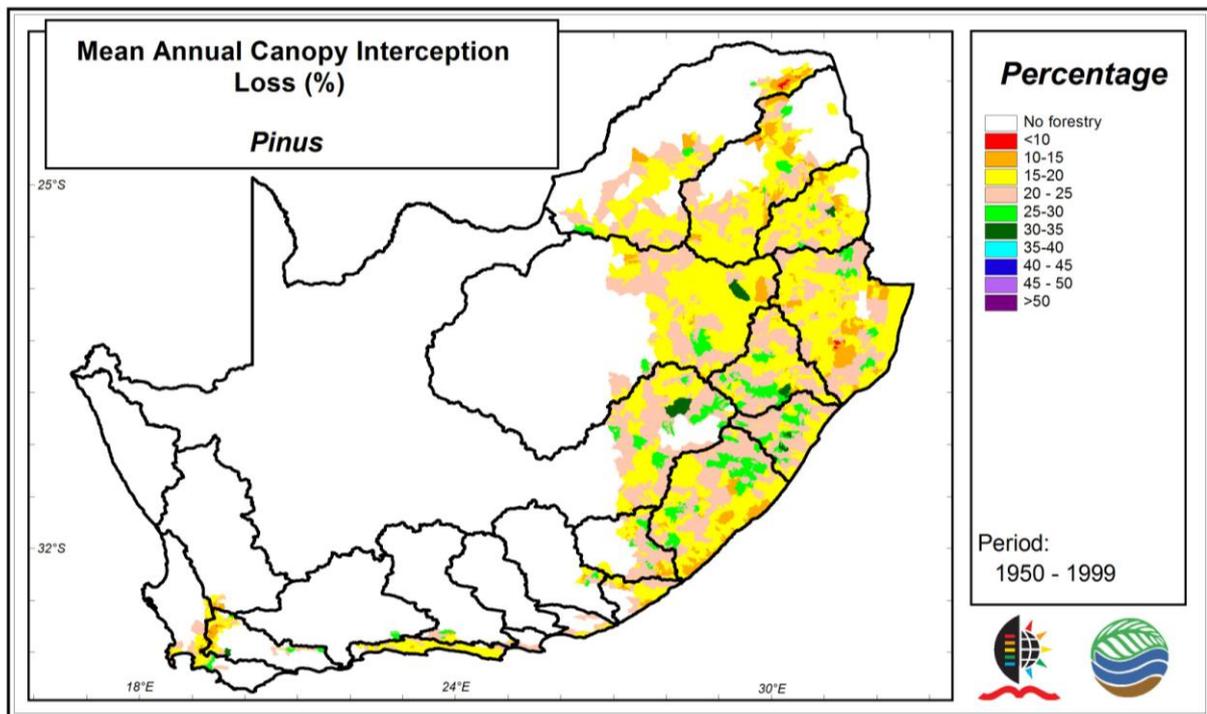
Figure 4.20   Representative mean annual canopy interception loss for *Pinus* as a percentage of gross precipitation per quinary catchment for South Africa.

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Canopy interception is most commonly expressed as a percentage of gross precipitation intercepted, as illustrated in Figures 4.8 to 4.10. Similar to Figures 4.5 to 4.7, canopy interception as a percentage of gross precipitation on the eastern side of the Drakensberg escarpment is generally higher than towards the west. On the eastern side, the canopy interception by *Eucalyptus* (Figure 4.8) is between 10% and 20% of gross precipitation. Towards the west of the escarpment canopy interception is similar to the eastern side, with most Q_nC's having a canopy interception of between 10% and 20% of gross precipitation. In the southern and south Western Cape, the canopy interception is variable, with some quinary catchments having less than 10% of the annual gross precipitation intercepted, but most are between 10 and 15% interception per year. The canopy interception by *Acacia mearnsii* is slightly higher than that of *Eucalyptus* and ranges between 15 and 30% per year. The canopy interception by *Pinus* is similar to that of *Acacia*, ranging between 10 and 30% per year. There are however, a few Q_nC's that have as much as 35% of the gross precipitation intercepted.
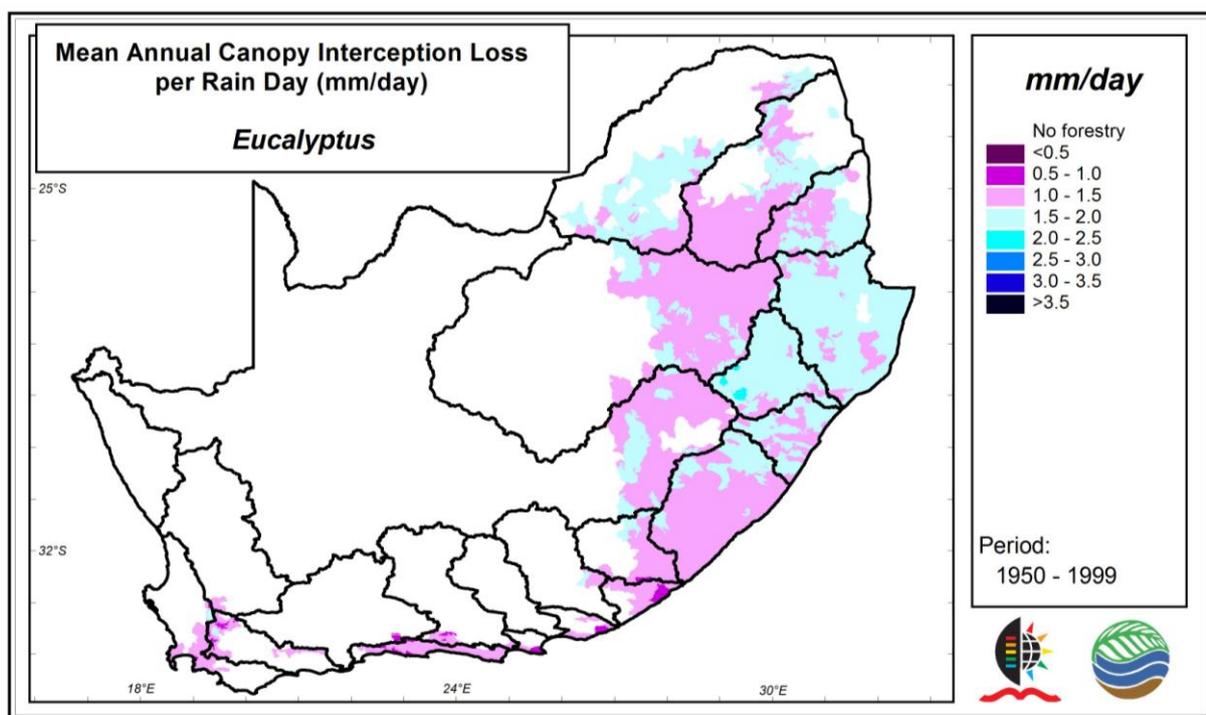
Figure 4.11   Representative mean annual canopy interception loss per rain day for *Eucalyptus* per quinary catchment for South Africa.
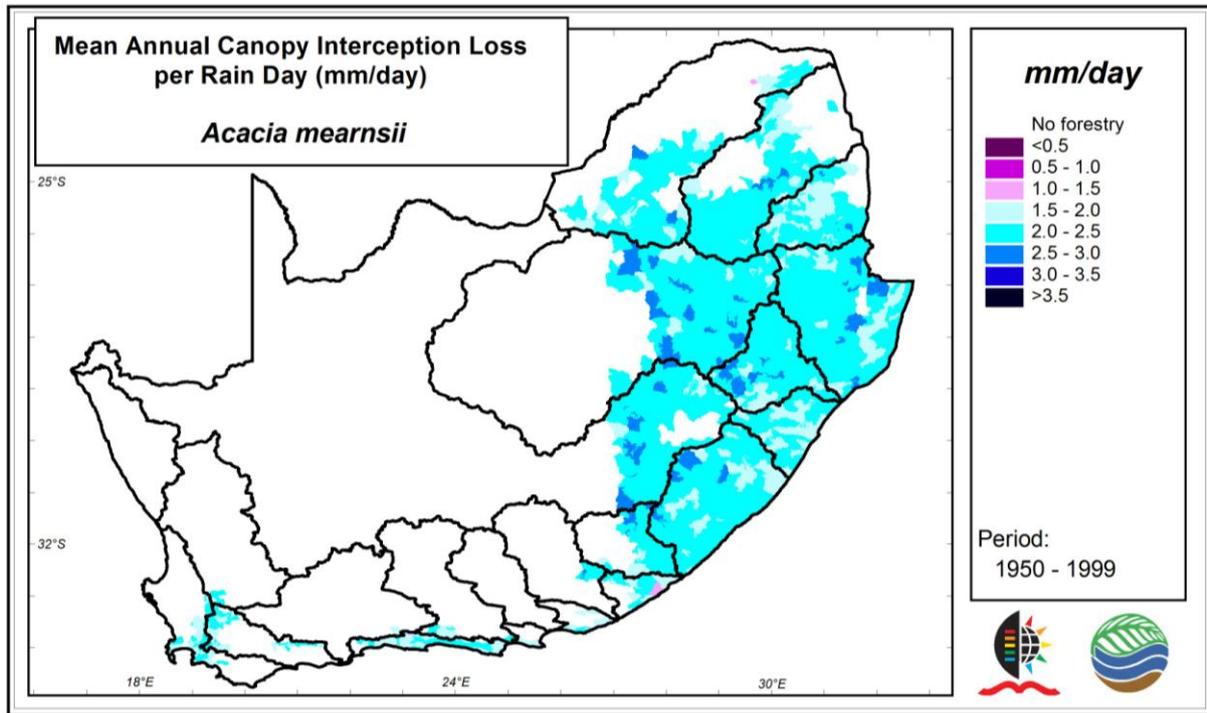
Figure 4.12   Representative mean annual canopy interception loss per rain day for *Acacia mearnsii* per quinary catchment for South Africa.
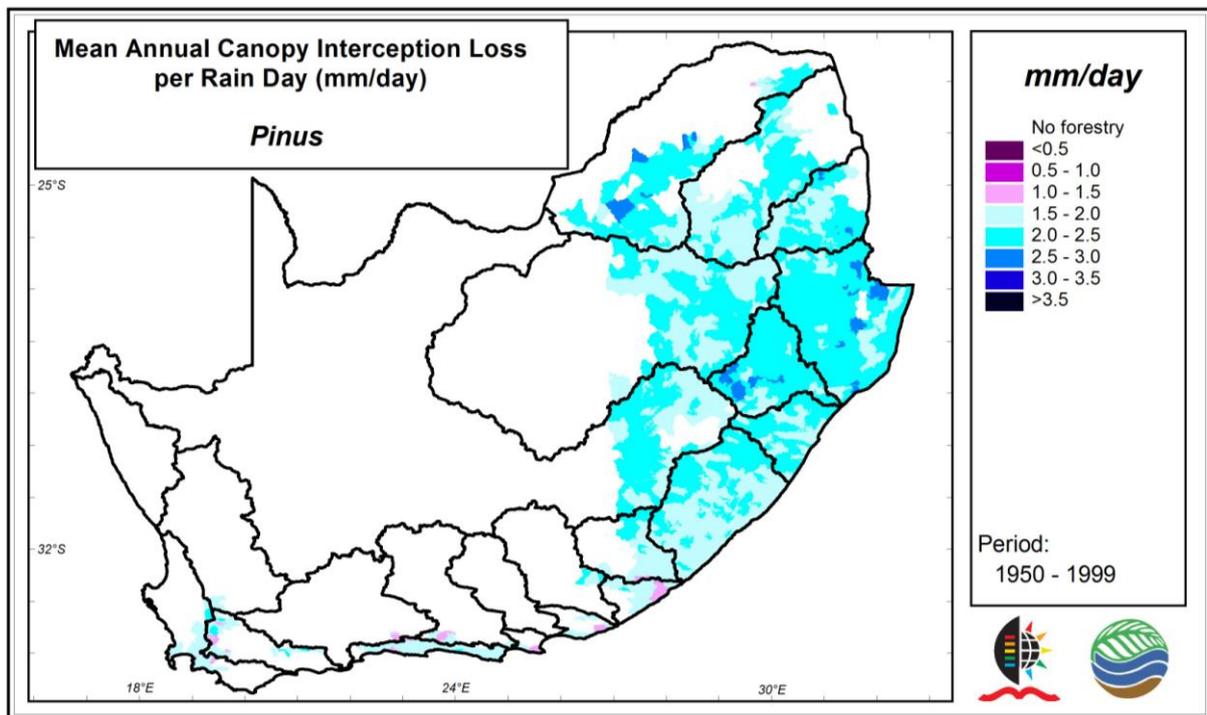
Figure 4.13   Representative mean annual canopy interception loss per rain day for *Pinus* per quinary catchment for South Africa.

A useful indication of canopy interception is the mean annual canopy interception per rain day as illustrated in Figure 4.11 to 4.13. Figure 4.11 illustrates that in the KwaZulu-Natal, Zululand and Mpumalanga forestry zones identified by Summerton, (1995), mean canopy interception per rain day is consistently between 1.5 and 2.0 mm for *Eucalyptus*. The mean interception loss per rain day for *Eucalyptus* in the Eastern Cape forestry zone is generally between 1.0 and 1.5 mm. The mean canopy interception loss per rain day for *Acacia mearnsii* is higher than that of *Eucalyptus*, with more values between 2.0 and 2.5 mm in all forestry zones. Similar to *Acacia*, the mean canopy interception per rain day for *Pinus* is generally between 1.5 and 2.5 mm per rain day, with some Q_nCs having between 2.50 and 3.0 mm per rain day.

4. CONCLUSION

From the results of this study, the early and mid summer rainfall regions which dominate the eastern half of South Africa have higher interception losses than the south and south Western Cape which are predominantly winter and all year rainfall regions. In the early and mid summer rainfall regions, interception ranges from less than 100 $mm.year^{-1}$ to 300 $mm.year^{-1}$ as opposed to the winter and all year rainfall regions which intercepts no more than 200 $mm.year^{-1}$. This may be explained by the fact that the early and mid summer rainfall regions have higher intensity rainfall events during the summer months when the evaporative potential is higher due to higher temperatures. Conversely, the winter and all year rainfall regions have lower intensity events of longer duration, as well as a lower evaporative potential due to lower temperatures. However, as a percentage of gross precipitation, early and mid summer regions as well as the winter and all year rainfall regions generally intercept between <10% and 35% of gross precipitation. There are however a few Q_nC's in the early and mid summer regions which intercept between 35 and 40% of the annual gross precipitation, suggesting that forestry grown in the early and mid summer regions generally intercepts more rainfall than that grown in the winter and all year rainfall regions.

This paper highlights the spatial distribution and variability of canopy interception as well as its significance in South African water resources management. The spatial variability of canopy interception is not only attributed to the varying LAI values in different areas, but also the variable rainfall intensity and seasonality. Therefore, without attempting to account for rainfall intensity and seasonality, the aim of this paper which was to assess the significance of canopy interception of commercial afforestation in South Africa would not have been fulfilled adequately as not all the processes driving canopy interception loss would have been considered. The high spatial variability of canopy interception illustrates the difficulty in finding "benchmark" values from literature as the same genus/species with similar LAI may have as much as a 100% difference in interception loss, depending on the location of the site. The variability in the amount of canopy interception for each

genus in this study is largely attributed to the different LAI values determined by Summerton (1995) and the water holding characteristics of the canopy which is defined by the elemental volume. These parameters in turn affect the canopy storage capacity which is a critical parameter in modelling canopy interception. The results from this study show that canopy interception is a significant component of the catchment water balance and is therefore an important consideration in water resources planning in South Africa. For this research to be of even greater value for water resources management and planning, an additional study to determine the "baseline" vegetations canopy interception is required. This would enable one to determine the difference in canopy interception between the "baseline" vegetation and the commercial forestry species. The results also highlight the variability of canopy interception depending on the genus and therefore LAI, as well as the area in which the trees are grown and the rainfall seasonality[3]. Therefore, canopy interception should not be modelled using over-simplified models that only consider LAI and gross precipitation. The approach taken to model canopy interception loss at the stand, catchment or national scale needs to be one that accounts for all factors that affect the canopy interception process but at the same time maintains a requisite simplicity by using parameters that are easily attainable.

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[3] The reader is referred to Appendices A to C. i.e. the mean monthly canopy interception for *Eucalyptus, Acacia* and *Pinus*, and Appendices D to F. i.e. mean monthly canopy interception per rain day maps for *Eucalyptus, Acacia* and *Pinus* respectively.

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CHAPTER 5

An investigation into the productive and non-productive green water-use of an indigenous *Podocarpus henkelii* stand in the KwaZulu-Natal Midlands.

An investigation into the productive and non-productive green water-use of an indigenous *Podocarpus henkelii* stand in the KwaZulu-Natal Midlands

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ABSTRACT

The production of biomass for direct human consumption such as food and timber is the largest human induced consumer of freshwater on Earth. There have been a number of studies undertaken in South Africa to quantify the green water-use (total evaporation) of introduced commercial forestry species that have shown conclusively that green water-use from commercial forest plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation. Green water can be categorised into productive (transpiration) and non-productive (canopy and litter interception and soil evaporation) green water fluxes. There is a widespread perception within South Africa that indigenous tree species, in contrast to commercial forestry genera/species, are water-wise and should be planted more extensively in view of their more efficient use of water. Information on the water-use of indigenous trees and forests is scarce and indirect, and the relative contributions of transpiration, canopy interception and litter interception to total evaporation have until now not been investigated in South Africa. The results from this study show that the productive green water use by *Podocarpus henkelii* and *Pinus patula* was 41.0% and 95.9% of gross precipitation respectively over the 18 month period of this study. The non-productive canopy and litter interception by *P. henkelii* accounts for 29.8% and 6.2% respectively, while canopy and litter interception accounted for 22.1% and 10.7% respectively for *P. patula*. The productive green water-use efficiency of *P. henkelli* and *P. patula* is 7.14g.mm^{-1} and 25.21g.mm^{-1} respectively, in comparison with the total green water-use efficiency of 3.8g.mm^{-1} and 18.8g.mm^{-1}. From a water resources management and planning perspective it is important to consider the total green water-use efficiency, but also to have a good understanding of the relative contributions of each component of the green water fluxes.

1. INTRODUCTION

The production of biomass for direct human consumption such as food and timber is by far the largest human induced consumer of freshwater on Earth (Falkenmark and Rockström, 2006). South Africa has a large area of exotic forest plantations that are planted in the wetter regions of the country, covering an area of approximately 1.4 million hectares compared with 0.5 million hectares covered by indigenous forests. The commercial forestry sector contributes approximately 22 billion rand to the South Africa economy and employs approximately 170 000 people (Chamberlain *et al*., 2005; DAFF, 2010). The "Green Water" approach was introduced by Falkenmark in 1995 (Falkenmark, 1995) and has since gained prominence as a highly effective way of highlighting the role of evaporation from the landscape (Jewitt, 2006). The consideration of Green Water flows in formal water resources planning is however proving to be very difficult (Jewitt, 2006). The term "Green Water" refers to all vapour fluxes and includes transpiration, soil evaporation, canopy interception and litter interception.

There have been a number of studies undertaken in South Africa to quantify the green water use (total evaporation) of introduced commercial forestry species. These studies have shown conclusively that green water use from commercial forest plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation (Dye, 1996; Scott *et al*., 2000). Thus, forest plantations have mostly reduced catchment water yields, and this has resulted in legislation limiting further afforestation in areas where water supplies are already committed. However, the demand for timber is growing strongly, yet the extent of the national forestry estate is essentially capped to minimise further declines in surface "blue water" resources (Dye *et al*., 2008). The reason for the production of biomass using more water than most other water–dependant processes is that water is a key element involved in plant growth. During the photosynthesis process, when the stomata are open to take in carbon dioxide, a large amount of water is simultaneously being transpired. While transpiration is considered a productive green water flow, it is accompanied by non-productive evaporative losses from the soil, litter and canopy should water be available to meet the atmospheric demand. Together, these vapour fluxes of transpiration, soil evaporation, and canopy and litter interception constitute the total green water-use in biomass production (Falkenmark and Rockström, 2006).

There is a widespread perception within South Africa that indigenous tree species, in contrast to commercial forestry genera/species including *Pinus* (pine), *Eucalyptus* (gum) and *Acacia mearnsii* (wattle), are water-wise and should be planted more widely in view of their more efficient use of water. This perception appears to be based on the observation that indigenous trees are generally slow growers, and the belief that growth rate and water-use are broadly linked. However, tree water-use, and the total evaporation from forests and woodlands, is difficult to measure, and so evidence of low water-use by indigenous trees is scarce and indirect. Many water use efficiency (WUE) studies express

water-use in terms of an increase in wood biomass relative to transpiration (productive green water-use). From the findings of a study by Dye *et al*., (2008) which considered the productive green WUE of indigenous species, it was found that the WUE of indigenous species is generally lower than that of commercial forestry species. Dye *et al*., (2008) defined WUE in their study as the increase in biomass per unit of water transpired. Although transpiration of the indigenous species was generally lower in comparison to more productive commercial species, particularly *Eucalyptus grandis,* the rate of growth was also much slower, hence a lower WUE. Dye *et al*., (2008) concluded that in general, indigenous trees appear to possess an advantage over commercial species in productive sites in their lower water-use and lower streamflow reduction impact, but not in growth rate. Because Dye *et al*., (2008) based their study on transpiration measurements only, the non-productive component of total evaporation (i.e. interception) was not considered. Information on the water-use of indigenous trees and forests is scarce and indirect, and the relative contributions of transpiration, canopy interception and litter interception to total evaporation have until now not been investigated in South Africa. The aims of this study are therefore:

1. To establish the relative contributions of transpiration, canopy interception and litter interception to total evaporation in an indigenous *Podocarpus henkelii* forest,

2. Determine the productive and non-productive green water-use of *P. henkelii*, and therefore,

3. Calculate the *total* green WUE of *P. henkelii*.

2.   METHODOLOGY

The objective of the measurement methodology was to determine the relative contributions of sapflow (transpiration), canopy interception and litter interception, as well as the "productive green water" and "total green water" WUE from an indigenous *Podocarpus henkelii* stand as shown in Figure 5.1. To achieve this, measurements were conducted for one year to incorporate seasonal variations and responses to climatic factors. Continuous sap flow (transpiration) monitoring on an hourly basis, together with event based measurements of canopy and litter interception was employed. Hourly measurements of a full suite of climatic variables (solar radiation, temperature, relative humidity, wind speed and rainfall), complemented these.
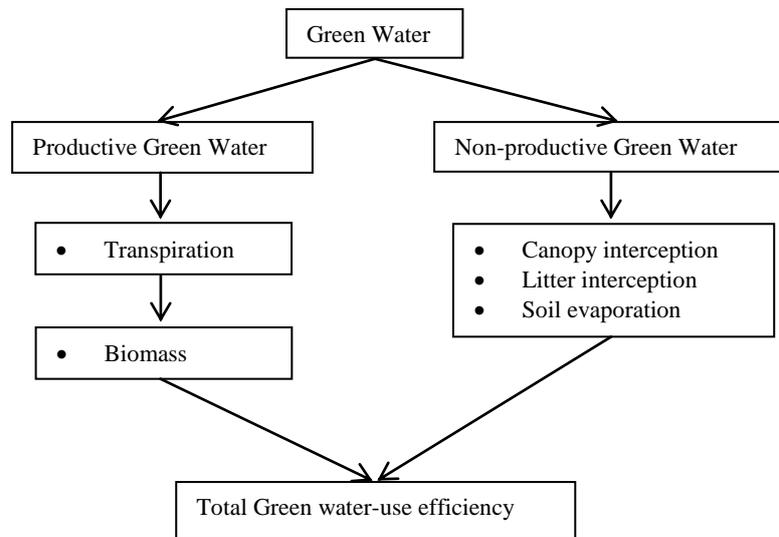
Figure 5.1   Schematic showing the components of productive and non-productive green water used to calculate total green water-use efficiency.

2.1   Site Description

Two study sites were selected on the Mondi owned Tetworth estate in Karkloof, near Howick in the KwaZulu-Natal Midlands (S 29° 21' 25.2" and E 30° 11' 49.3", alt. 1148 m.a.s.l) and has a mean annual precipitation of 1271 mm (Lynch and Schulze, 2006), most of which falls during the summer months between October and April. Mucina and Rutherford (2006) describe the area as southern mistbelt forest. A characteristic of the rainfall regime is a strong orographic effect, caused by the lifting and convective cooling of the summer south-east winds over the Karkloof mountain range (Dye *et al*., 2008). During the 547 day study period from October 2009 to March 2011, a total of 1635.9mm of rainfall was recorded, of which 346 days had rainfall. The first site was a small (<1ha) indigenous *Podocarpus henkelii* site that was located in a riparian area. *Podocarpus henkelii* are evergreen and have long slender drooping leaves (Palgrave, 2002). Details on the stand are limited due to changes in ownership of this particular farm, and the trees are of an unknown age. However, by virtue of their

size (average tree height of 8m) and stem diameters (DBH: 15-30cm) the trees are estimated to be roughly 40 years old. The trees were hand planted, but have not actively been pruned. The planting spacing is somewhat irregular but an average distance between trees (3 m x 3 m) translates into a planting density of approximately 1111 trees per hectare. The second site is a commercial plantation *Pinus patula* stand grown for saw timber with a planting density of 816 trees per hectare (3.5m x 3.5m).

2.2 Tree Samples

The sap flow and stem increment rates were measured by Gush *et al*., (2011) in two trees at this site (Table 5.1). Bark thicknesses of the sample trees were determined by excising bark sections from the stems. Measurements of sapwood depth, required to determine the insertion depths of thermocouple probes for water-use measurements, were obtained using a 5mm inside-diameter increment corer (Haglöf, Sweden). Cores were subsequently analysed for sapwood depth using measurements of the visual distinction between lighter coloured sapwood and darker coloured heartwood. Wood density for the two tree species was determined using mass and volume measurements (Archimedes Principle) on stem-wood samples chiselled from the trees. Monitoring began on 13 August 2009 and continued until the end of March 2011. The canopy and litter interception monitoring began at the beginning of the wet season in October 2009.

Table 5.1   Sample tree details as of 12 August 2010.

Tree	Diameter at Breast height (mm)	Tree height (m)	LAI	Sapwood depth (mm)	Wound width (mm)	Bark width (mm)	Wood density (g.cm^{-3})	Mean litter thickness (mm)
P.henkelii 1	140	6.34	3.5	55	3	7	0.468	52
P.henkelii 2	230	7.33	4.0	95	3	7	0.468	52
P. patula 1	200	8.77	2.3	85	4	10	0.380	151
P. patula 2	240	10.79	2.5	100	4	10	0.380	151

2.3 Canopy Interception

Throughfall measurements were undertaken at the *Podocarpus henkelii* site using a nest of three "V" shaped troughs based on the design of Cuartus *et al*., (2007) constructed from galvanised sheeting. The dimensions of each trough are 0.1 m wide x 2.0 m long. Conventional "U" or "V" shaped troughs were susceptible to blockage by fallen debris and water loss from splash out, however, this system minimizes splash out by using steep "V" shaped sides. The troughs were covered with mosquito

netting to minimize the entry of debris, which reduced the demand of cleaning and maintaining the system. The troughs were then connected to a tipping bucket gauge and an event data logger. Because the trough represents a linear and continuous sampling surface, the linear variation of leaves, branches, and tree crown, it is assumed to be a representative integral of the throughfall caught (Cuartus *et al.*, (2007).

2.4   Litter Interception

The litter interception and water that drains to the soil were measured at the *Podocarpus henkelii* site using two round galvanized iron basins that fit into each other. The upper basin which has a diameter of 500mm is filled with litter and has a geotextile lining on top of a wire mesh base, so water can percolate into the lower basin. The water that is collected in the lower basin drains into a tipping bucket and records the water that would have drained to the soil. The litter interception is then calculated as the difference between throughfall and the water that drained to the soil.

2.5   Canopy and Litter Interception Models

Due to the unavailability of canopy and litter interception data for the *P. patula* stand at the Karkloof site, the "variable storage Gash model" and idealised drying curve models (*cf*. Chapter 3) were used to model canopy and litter interception respectively for *P. patula*. These models are described in detail in Chapter 3.

2.6   Sap Flow Measurements

The Heat Pulse Velocity (HPV) technique is an internationally accepted method for measuring the flow of sap in trees and has received much attention by researchers in recent years, (Smith and Allan, 1996; Gush and Dye, 2009). The HPV technique was used to measure the sapflow/transpiration for both *Podocarpus henkelii* and *Pinus patula*. The HPV measurements described in this paper are based on the heat ratio method (HRM) described by Burgess *et al*. (2001) because of its ability to accurately measure low rates of sap flow that were expected to be the case in the indigenous *Podocarpus henkelii* stand. The HPV technique has been extensively applied in South Africa (Dye & Olbrich, 1993; Dye, 1996; Dye, Soko & Poulter, 1996; Dye *et al.*, 1996; Gush, 2008; Gush & Dye, 2009). The HRM requires a line-heater to be inserted in the xylem at the vertical midpoint (commonly 5 mm) between two temperature sensors (thermocouples). Heat pulses are used as a tracer, which is carried by the flow of sap up the stem. This allows the velocity of individual heat pulses to be determined by recording the

ratio of the increase in temperature measured by the thermocouples (TC's), following the release of a pulse of heat by the line heater. For these measurements TC pairs and heater probes were positioned 80cm up the main stem of each tree, below the first branches. TC's were inserted to four different depths within the sapwood to determine radial variations in sap flow. The insertion depths of the TC's were calculated after first determining the total sapwood depth for each species, and then spacing the probes evenly throughout. All drilling was performed with a battery-operated drill using a drill guide strapped to the tree, to ensure that the holes were as close to parallel as possible. CR1000 data loggers connected to AM16/32 multiplexers (Campbell Scientific, Logan, UT) were programmed to initiate the heat pulses and record hourly data from the respective TC pairs.

Heat pulse velocities derived using the HRM were corrected for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson & Whitfield (1981). The corrected heat pulse velocities were then converted to sap flux densities according to the method described by Marshall (1958). Finally, the sap flux densities were converted to whole-tree total sap flow by calculating the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). Hourly sap flow values were recorded from all the trees. Periods of missing data were patched and the complete record was aggregated into daily, monthly and annual totals. Individual tree sap flow volumes ($L.month^{-1}$) were scaled up to a hectare using the planting density to also derive sap flow (transpiration) totals in mm-equivalent volumes (Gush *et al*., 2011).

2.7 Stem Growth Measurements

In addition to sap flow measurements, stem biomass increments surveys were undertaken for both *P. henkelii* and *P. patula*, in order to calculate WUE. Stem biomass increment measurements were carried out at the inception of the study on the 13 August 2009 and subsequently a year later on the 12 August 2010 in order to incorporate a 1-year seasonal variation. Stem circumferences were measured at increasing heights up the tree, and subsequently converted into volume by assuming that the stem consists of a series of truncated cones with a complete cone on the top. The volumes (*V*) (m^3) of the individual cones was calculated using Equation 5.1.

$$V = (\pi.r^2.h)/3 \tag{5.1}$$

Where, *r* is the radius at the base of the cone (m), and *h* is the height of each cone (m).The volumes of the truncated cones were calculated using Equation 5.2.

$$V = [\pi.h(r_1{}^2 + r_1r_2 + r_2{}^2)]/3 \tag{5.2}$$

Where, r_1 is the radius at the base of the truncated cone (m), r_2 is the top of the truncated cone (m), and h is the height of the truncated cone (m).

The stem biomass increments were converted from volumes to mass using the wood densities determined for each species as shown in Table 5.1.

3.   RESULTS

The results discussed in the subsequent sections are for the period of October 2009 to March 2011 at the *Podocarpus henkelii* and *Pinus patula* stands in Karkloof.

3.1   Relative Contributions of Transpiration, Canopy and Litter Interception.

The transpiration (Sap flow) recorded in the *P. henkelii* stand shows a relatively consistent rate throughout the year (Figure 5.2) with monthly transpiration varying between 26.8mm and 48.8mm. This may be attributed to the evergreen nature of *P. henkelii*, as well as the lack of seasonal water stress due to the riparian location of the site. The highest sap flows are recorded during the summer months when leaf area, temperature and available water increase. Transpiration accounts for the largest green water use at 41% and 95.9% of the gross precipitation for both *P. henkelii* and *P. patula* respectively during the study period (Table 5.2). Canopy interception is the second highest green water use at 29.8% and 22.1% of gross precipitation for *P. henkelii* and *P. patula* respectively. The highest monthly canopy interception loss for both *P. henkelii* and *P. patula* was recorded in December 2009 at 50.4mm and 37.2mm respectively. The highest canopy interception losses are expected during the summer months when there is the greatest rainfall, as well as highest evaporation potential due to the highest temperatures. Conversely, the lowest canopy interception losses are recorded during the winter months when there is very little rainfall, with as little as 3.7mm and 2.7mm being lost to canopy interception in May 2010 for *P. henkelii* and *P. patula* respectively. Litter interception is the lowest green water use, accounting for only 6.2% and 10.7% of gross precipitation for *P. henkelii* and *P. patula* respectively. The small litter interception amount can be attributed to the large number of consecutive raindays, during the rainy summer months, thereby not allowing time for much evaporation to take place. The trees also have a dense canopy with an LAI of between 3.5 and 4.0 for *P. henkelii* and between 2.3 and 2.5 for *P. patula*, and therefore not allowing much solar radiation to reach the litter to aid in evaporation. During the winter months, there is little rainfall, and after canopy interception losses have been accounted for, there is little throughfall to be intercepted by the litter.
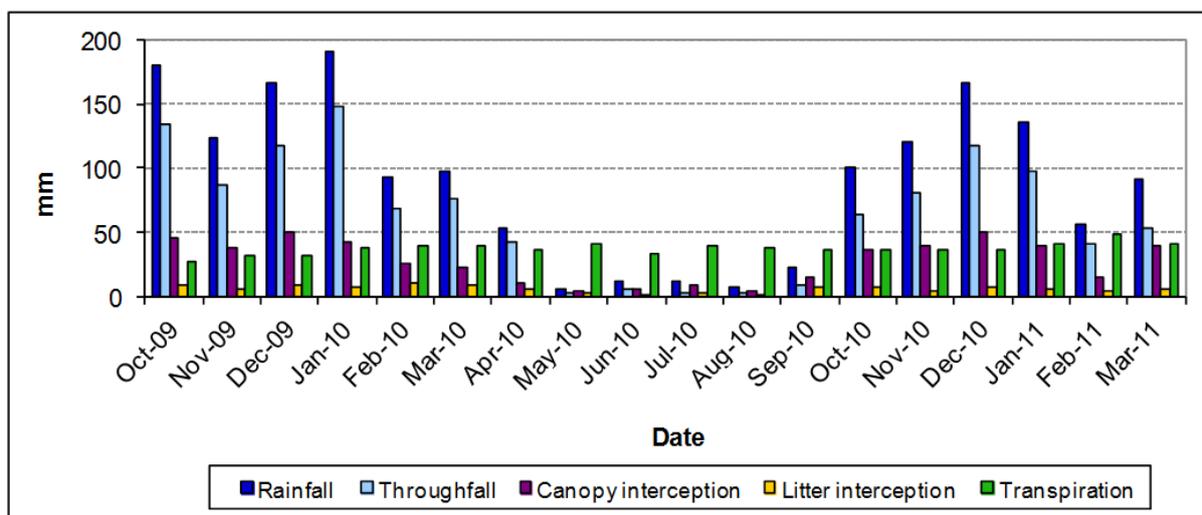
Figure 5.2   Measured contributions of rainfall, throughfall, canopy interception, litter interception and transpiration for the period October 2009 to March 2011 for *P. henkelii*.

Table 5.2   Monthly contributions and totals of rainfall, throughfall, canopy interception, litter interception and transpiration measured for the period October 2009 to March 2011 for *P. henkelii*.

Date	Rainfall (mm)	Throughfall (mm)	Observed canopy interception (mm)	Observed litter interception (mm)	Transpiration (mm) *P. henkelii*
Oct-09	179.6	134.5	45.1	8.9	26.8
Nov-09	123.6	86.2	37.4	5.2	32.2
Dec-09	167.2	116.8	50.4	9.0	32.3
Jan-10	190.6	148.8	41.8	7.3	37.2
Feb-10	93.1	68.0	25.1	9.9	39.0
Mar-10	98.3	76.3	22.0	9.2	39.1
Apr-10	53	42.5	10.5	6.2	36.2
May-10	6.1	2.4	3.7	1.9	40.3
Jun-10	11.6	5.7	5.9	1.5	33.8
Jul-10	11.5	3.3	8.2	2.0	39.0
Aug-10	7.6	2.7	4.9	1.0	38.3
Sep-10	22.1	8.2	14.9	7.0	36.2
Oct-10	100.4	63.7	36.7	7.9	36.2
Nov-10	120.2	80.7	39.5	3.6	36.7
Dec-10	166.4	116.9	49.5	7.3	36.0
Jan-11	135.9	97.1	38.8	5.3	41.3
Feb-11	56.6	41.5	15.1	3.5	48.8
Mar-11	92.1	53.4	38.7	5.1	40.8
Total (mm)	1635.9	1148.8	488.1	101.8	670.3
Percentage (%)		70.2	29.8	6.2	41.0

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Table 5.3   Monthly contributions and totals of rainfall, throughfall, modelled canopy interception, modelled litter interception and transpiration for the period October 2009 to March 2011 for *P. patula*.

Date	Rainfall (mm)	Throughfall (mm)	Modelled canopy interception (mm)	Modelled litter interception (mm)	Transpiration (mm) *P. patula*
Oct-09	179.6	129	33.3	17.3	66.0
Nov-09	123.6	85.8	27.6	10.2	73.5
Dec-09	167.2	112.6	37.2	17.4	82.7
Jan-10	190.6	145.5	30.9	14.2	94.3
Feb-10	93.1	65.4	18.5	9.2	124.2
Mar-10	98.3	71.3	16.2	10.8	113.6
Apr-10	53	33.2	7.8	12.0	93.9
May-10	6.1	1.7	2.7	1.7	104.2
Jun-10	11.6	4.3	4.4	2.9	67.3
Jul-10	11.5	1.5	6.1	3.9	62.5
Aug-10	7.6	2.1	3.6	1.9	79.6
Sep-10	22.1	1.6	11.0	9.5	74.8
Oct-10	100.4	58	27.1	15.3	71.7
Nov-10	120.2	84	29.2	7.0	79.6
Dec-10	166.4	115.8	36.5	14.1	76.7
Jan-11	135.9	97	28.6	10.3	94.7
Feb-11	56.6	38.6	11.1	6.9	109.4
Mar-11	92.1	53.6	28.6	9.9	101.1
Total (mm)	1635.9	1101.0	360.4	174.5	1569.8
Percentage (%)		67.3	22.1	10.7	95.9

3.2   Productive Green Water Use Efficiency

The stem growth and water-use efficiency for the two *P. henkelii* and *P. patula* trees was calculated for the one year period 13 August 2009 to 12 August 2010 (Gush *et al*., 2011) and is summarised in Tables 5.4 and 5.5. The WUE was calculated as the increase in stem wood mass relative to transpiration (productive green water). The WUE was also calculated as a mm-equivalent by considering the planting density of 1111 and 816 stems per hectare for *P. henkelii* and *P. patula* respectively. From Tables 5.4 and 5.5 it can be seen that the average productive WUE of the two *P. henkelii* trees is 0.79 g.L^{-1} or 7.14g.mm^{-1} transpired and 2.06g.L^{-1} or 25.21g.mm^{-1} for *P. patula*.

Table 5.4   Summary of productive WUE data for *P. henkelii* trees as calculated from a mass-based ratio of biomass increment relative to productive green water-use for the one year period 13 August 2009 to 12 August 2010.

Tree	1yr water-use (L)	1yr water-use (mm)	Stem Volume increment (m^3)	Wood Density (g.cm^{-1})	Stem mass increment (g)	WUE (g stem wood.L transpired water^{-1})	WUE (g stem wood.mm transpired water^{-1})
P. henkelii 1	1755	195.0	0.00215	0.468	1006.2	0.5733	5.16
P. henkelii 2	5033	559.2	0.01088	0.468	5091.8	1.0117	9.11
Average	**3394**	**378.6**	**0.00652**	**0.468**	**3049.0**	**0.7925**	**7.14**

Table 5.5   Summary of productive WUE data for *P. patula* trees as calculated from a mass-based ratio of biomass increment relative to productive green water-use for the one year period 13 August 2009 to 12 August 2010.

Tree	1yr water-use (L)	1yr water-use (mm)	Stem Volume increment (m^3)	Wood Density (g.cm^{-1})	Stem mass increment (g)	WUE (g stem wood.L transpired water^{-1})	WUE (g stem wood.mm transpired water^{-1})
P. patula 1	9849	803.7	0.05157	0.380	19596.6	1.9897	24.23
P. patula 2	16067	1311.1	0.09035	0.380	34333.0	2.1369	26.19
Average	**12958**	**1057.4**	**0.07096**	**0.380**	**26964.8**	**2.0633**	**25.21**

3.3   Total Green Water-Use Efficiency

Using the average mm-equivalent productive green WUE of the two *P. henkelii* and *P. patula* trees of 7.14g.mm^{-1} and 25.21g.mm^{-1} transpired water respectively, as shown in Tables 5.4 and 5.5, the stem mass increment for the period October 2009 to March 2011 can be estimated and therefore, the total green water WUE was determined as shown in Table 5.6.

Table 5.6   Summary of WUE data for *P. henkelii* and *P. patula* trees as calculated from a mass-based ratio of biomass increment relative to total green water-use for the period October 2009 to March 2011.

Tree	Average productive WUE (g.mm transpired^{-1})	Transpiration (mm)	Stem mass increment (g)	Canopy interception (mm)	Litter interception (mm)	Total Green water (mm)	Total Green WUE (g.mm total green water^{-1})
P. henkelii	7.14	670.3	4785.9	488.1	101.8	1260.2	3.8
P. patula	25.21	1569.8	39574.7	360.4	174.5	2104.7	18.8

After calculating the average stem mass increment for the period of October 2009 to March 2011 by multiplying the average productive WUE by the transpiration, the total green WUE was calculated. In order to calculate the total green WUE, the stem mass increment was divided by the sum of all green water fluxes (transpiration, canopy and litter interception). When the total WUE is calculated by considering all the green water fluxes, the WUE of *P. henkelii* is 3.8g.mm^{-1} as opposed to 7.14g.mm^{-1}, which is a difference of 46.8%. Similarly, the total WUE of *P. patula* is 18.8g.mm^{-1} as opposed to 25.21g.mm^{-1}, which is a difference of 26.2%, highlighting the large difference in the two approaches of calculating WUE.

3. DISCUSSION AND CONCLUSION

Many WUE studies express water-use in terms of an increase in wood biomass relative to transpiration (productive green water-use). While this approach is useful in terms of a physiological water-use, it may be misleading for water resources management and planning. For example, two different crops/trees may have similar productive green water-use efficiencies, but one may have a significantly higher or lower canopy and litter interception than the other resulting in a different total green WUE. As shown in the results of this research, the difference between productive green WUE and total green WUE where the non-productive green water fluxes are included is 46.8% and 26.2% for *P. henkelii* and *P. patula* respectively. Therefore, for the total green water-use efficiency approach to be implemented in more studies, there is a need for good canopy and litter interception models that make use of readily available data that can be used in cases where interception data are not available.

In terms of productive green WUE, introduced species such as *Pinus patula* may be 2-4 times more efficient in their water-use than *P. henkelli*, based on the results of other studies (Olbrich *et al*., 1996; Dye *et al*., 2001; Gush and Dye, 2009; Gush *et al*., 2011), which correspond well with the findings on this study. While the indigenous *P. henkelii* may not be as water-use efficient as some introduced plantation species, it does have a relatively lower water-use year on year, if the increase in biomass is not considered (i.e. lower total green water flux). This is important from a water resources management perspective, where the harvesting of timber is of secondary importance, as the indigenous species will have a lower annual reduction in streamflow than introduced plantation species. From a hydrological or water management point of view, a potential application of indigenous species could be in the planting of them in riparian areas within commercially afforested areas as is the case at the site of this study. Many of the narrow riparian areas of grassland that remain after commercial afforestation are heavily infested with alien invasive species due to the difficultly in managing them. As it is dangerous to perform bi-annual burns within the plantation, it may be a viable land-use option to plant indigenous trees species in these areas due to their low water-use (Gush *et al*., 2011). However, when considering the impact of planting trees within a riparian area, the productive and

non-productive green water use should be considered, as it is the total green water use that will ultimately determine the streamflow reduction as well as the water resource management and planning decision.

While it is the total green water flow that needs to be considered from a water resources management and planning perspective, one cannot lose sight of the importance of considering the individual components of productive and non-productive green water. The non-productive components of total evaporation have been referred to by some as "white water" (Savenije, 2004), highlighting that hydrologically it is problematic to lump these two components and that there needs to be clear recognition that these components need to be considered separately in hydrological process studies. Failure to have a sound conceptual understanding of the individual components that make up total green water flows may lead to modelling efforts being compromised (Jewitt, 2006). Therefore, this paper highlights the importance of considering the individual components of both productive and non-productive green water flows, and in particular, the role that interception plays in the hydrological cycle and that from a water resources management and planning point of view, the total green water-use efficiency needs to be considered. However, it is still vitally important to understand the productive water-use efficiency for the optimisation of future water, food and timber requirements.

Acknowledgements

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CHAPTER 6

Spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on canopy interception

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Spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on canopy interception[4]

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ABSTRACT

The establishment of commercial forestry plantations in natural grassland vegetation, results in increased transpiration and interception which in turn, results in a streamflow reduction. Methods to quantify this impact typically require LAI as an input into the various equations and process models that are applied. The use of remote sensing technology as a tool to estimate leaf area index (LAI) for use in estimating canopy interception is described in this paper. Remote sensing provides a potential solution to effectively monitor the spatial and temporal variability of LAI. This is illustrated using Hyperion hyperspectral imagery and three vegetation indices, namely the normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI) and Vogelmann index 1 to estimate LAI in a catchment afforested with _Eucalyptus, Pinus_ and _Acacia_ genera in the KwaZulu-Natal midlands of South Africa. Of the three vegetation indices used in this study, it was found that the Vogelmann index 1 was the most robust index with an R^2 and root mean square error (RMSE) values of 0.7 and 0.3 respectively. However, both NDVI and SAVI could be used to estimate the LAI of 12 year old _Pinus patula_ accurately. If the interception component is to be quantified independently, estimates of maximum storage capacity and canopy interception are required. Thus, the spatial distribution of LAI in the catchment is used to estimate maximum canopy storage capacity in the study area.

Keywords: Remote sensing, leaf area index, canopy interception, maximum storage capacity.

1. INTRODUCTION

To the water resources planner who is ultimately interested in the amount of water available, the vegetation canopy is a barrier for precipitation to cross before reaching the soil and possibly making its way to the river or dam (Davies, 2003). In South Africa, it has been estimated that commercial forestry uses about 5% of the total available water supply (GCIS, 2007). By virtue of their physiology, extent of coverage and location in the high rainfall catchment areas of South Africa, commercially grown tree species impact on the hydrological resources of the country with an even more significant impacts at smaller spatial and temporal scales. Between 1986 and 1998, the area under forestry in South Africa increased by 27% to 1.44×10^6 ha, which constitutes 1.18% of the arable land (Gush, 2000), but is reported to have decreased to approximately 1.27×10^6 ha over the past five years, because of fire and withdrawal of some land from production (Godsmark, 2008).

Vegetation cover or land cover influences hydrological processes in many ways. Interception and transpiration is a loss or sink term in the water balance of a catchment, and evaporation and transpiration losses have been shown to influence downwind rainfall at regional scales (Shultz and Engman, 2000). Forest stand description typically includes factors related to the eco-physiological processes responsible for forest growth. One of those factors is the stand leaf area index (LAI). LAI is related to processes such as canopy interception, transpiration, photosynthesis, and leaf litterfall, and used as an input to various ecosystem and hydrological models (Sprintsin *et al*., 2007) such as the ACRU Agrohydrological model (Schulze, 1995), the 3PG model (Landsberg and Waring, 1997) and SIMPLE model (Hörmann, 2007). Nemani *et al*., (1993) found that LAI varies with microclimate and soil water conditions. In their study, hilltops showed a lower LAI owing to less available water and therefore more stress, while the bottom of hill slopes had more water, less stress, higher temperatures, possibly more nutrients, and therefore higher LAI values.

Accurate monitoring and assessment of water resources is necessary for sustained water resource management. Earth observation data have formed the basis for acquiring data remotely for many years (Landgrebe, 1999) and are now viewed as a time and cost-effective way to undertake large-scale monitoring (Okin *et al*., 2001). Remote sensing has been widely recognised as a valuable tool for the detection and analyses of data, both spatially and temporally, with significant advantages over point sources (Bongonko, 2005) and is becoming increasingly useful in southern Africa, where components of the hydrological cycle, such as rainfall, evaporation, plant water use and runoff show great variation in both time and space (Jewitt, 2002), and where traditional monitoring is extremely limited. The past decade has seen a particularly rapid increase in the number of launched satellites, as well as an improvement in both spatial and spectral resolution of data they produce. The planned launch of several new satellites will lead to further improvements in the quality of remotely sensed data (Dye *et*

al., 2002). The ability to rapidly assess LAI using vegetation indices (VIs) from remotely sensed imagery provides a means to rapidly assess stand productivity over a wide geographic area. There are a growing number of studies that are using hyperspectral remote sensing to estimate the LAI of forest and crop canopies such as those by Delegido *et al*., (2008), Haboudane *et al*., (2004) and Zhang *et al*., (2005). In addition to providing alternative means to estimate forest productivity in the long term, this approach may complement existing approaches aimed at estimating water use of various crops in fulfilment of the National Water Act of 1998. The Act makes provision for the classification of various crops and land use practices as streamflow reduction activities (SFRA), which are then subject to controls to ensure equity in water allocation (Ghebremicael *et al*., 2004). Current tools to assess water use by commercial afforestation tend to focus on total evaporation and are limited in their consideration of interception from forest canopies as a separate process.

In this study, data from the Hyperion sensor on board the EO-1 satellite, the first hyperspectral sensor to operate from space was used to estimate LAI in a small afforested catchment in the KwaZulu-Natal Midlands of South Africa. The satellite estimates were verified using measurements obtained from the field site using a handheld LI-COR LAI-2000 plant canopy analyzer. The information from this analysis was then used to map interception storage capacity over the same area. Ultimately, this approach will provide for better spatial estimation of canopy interception, which is a little studied aspect of forest water use in South Africa. The images used in this paper are those used for the Water Research Commission (WRC) Report 1684/1/08, which was a project that looked at methods of classifying vegetation. The project focused on developing a method which could be used on any image at any time of the year, and hence only a single image is required. Similarly, this paper is aimed at developing a method for estimating LAI rather than looking at the temporal variations, which only requires a single image.

2. CANOPY INTERCEPTION AND LEAF AREA INDEX

Interception is one of the most neglected and underestimated processes in rainfall-runoff analysis. Some models disregard it completely, based on the assumption that it is generally a small portion of the total evaporation (Savenije, 2004). However, Beven (2001) states that evaporation from intercepted water on leaf surfaces in rough canopies can be very efficient and could form a significant component of the total water balance in some environments. In a forest with a closed canopy, the interception of precipitation is a major component of the influence that forests exert on the hydrological cycle (Jewitt, 2005) and may be simply defined as the difference between gross rainfall and net rainfall (net rainfall being the sum of stemflow and throughfall). A broader definition by Savenije (2004) is that interception accounts for the part of the rainfall that is captured before it can

take part in the subsequent runoff and sub-surface processes. This definition is more useful for hydrological modelling, where the focus is surface runoff, the soil moisture budget, transpiration, recharge and ground water processes.

Interception loss from forests depends on the atmospheric conditions that drive evaporation and rainfall characteristics, but also the nature and density of the forest stand. This depends on the tree physiology, but also management practice and the age of the trees, older trees have denser canopies and correspondingly higher canopy storage, and higher interception loss than younger trees (Jewitt, 2005). The dependence of the storage capacity on the LAI is highlighted by considering Eq. (6.1) developed by von Hoyningen-Huene (1981) which is still recognised as an accurate, non-crop specific estimate of maximum storage capacity (S^c_{max}) (mm) as highlighted by Kozak $et\ al$., (2007).

$$S^c_{max} = 0.935 + 0.498(LAI) - 0.00575(LAI^2) \tag{6.1}$$

The subsequent process of throughfall is the water that falls to the ground either directly through gaps in the canopy, or indirectly by having dripped off leaves, stems and branches after the storage capacity has been reached. The amount of direct throughfall and, conversely indirect throughfall is controlled by the canopy coverage (c), a measure of which is the LAI (Davies, 2003).

Van Dijk and Bruijnzeel (2001a, 2001b) modified the well-known Gash $et\ al$., (1995) revised model allowing it to be applied to rapidly growing vegetation where the LAI is changing through time. For this model, LAI is defined as the cumulative one-sided area of (healthy) leaves per unit area. LAI and c, can be related to one another via the Beer-Lambert equation which describes the attenuation of radiation (i.e. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate far through leaves, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between c and LAI is thus given by Eq. (6.2).

$$c = 1 - e^{-K.\ LAI} \tag{6.2}$$

Where K is the extinction coefficient. The value of K for a particular radiation wavelength depends on the inclination angle and distribution of the leaves, and for PAR usually ranges between 0.6 and 0.8 in forests (van Dijk and Bruijnzeel, 2001a, 2001b).

The water that is retained on the leaves is then evaporated from the wet canopy surface, which has been found to evaporate at rates in excess of available net radiation and potential evaporation because of advection and the low aerodynamic resistance of wet canopies (Schulze, 1995; Davids $et\ al$., 2005).

Equation (6.3) provides a conservative estimate of enhanced wet canopy evaporation rate, E_w (mm.day^{-1}) (Schulze, 1995), which incorporates LAI as a governing parameter.

$$E_w = E_r(0.267LAI + 0.33) \text{ for } LAI > 2.7 \tag{6.3}$$

Where:

E_r - A-pan equivalent reference potential evaporation (mm.day^{-1})

LAI - Leaf area index (dimensionless)

By implication, wet canopy evaporation proceeds at a rate of 1.67 times that of potential evaporation for LAI = 5.

Considering canopy interception is dependant on the storage capacity (S_c), canopy cover (c) and wet canopy evaporation (E_w), all of which are related to the LAI. Von Hoyningen-Huene (1983) in Schulze (1995) developed Eq. (6.4) based on extensive research conducted on a number of agricultural crops and related their interception loss (mm.day^{-1}) to gross daily rainfall (P_g) and LAI as:

$$I_l = 0.30 + 0.27P_g + 0.13LAI - 0.013P_g^2 + 0.0285Pg.LAI - 0.007LAI^2. \tag{6.4}$$

The LAI and gross precipitation are used as the canopy structure and climatic descriptors respectively. Although the equation was developed for agricultural crops, Schulze (1995) found that the equation performed well on *Pinus patula*, and therefore it was deduced that the Von Hoyningen-Huene approach has potentially widespread application and is encouraged as the interception loss estimator in the ACRU agrohydrological model (Schulze, 1995).

3. METHODOLOGY

3.1 Site Description

The Mistley-Canema estate is situated in the Seven Oaks district in the KwaZulu-Natal Midlands, South Africa as shown in Figure 6.1. According to Camp (1997) the South African Bioresource Group (BRG) is "moist midlands mistbelt". The climate is humid, with an annual rainfall ranging from 800mm to 1280mm per annum and the mean annual temperature is 17°C. The natural vegetation of the area was previously indigenous *Themeda triandra* grassland. Only a few relic patches of *Themeda triandra* grassland remain, as the high potential of the arable areas has meant that little value has been placed on the natural vegetation. Commercial afforestation has long been practiced in the area and is the most widespread land use, with gum (*Eucalyptus*), pine (*Pinus*) and wattle (*Acacia*) being the species of choice. Sugarcane is also grown at sites where drainage of cold air is good, ensuring that no frost or only light frost occurs (Everson *et al*., 2006).
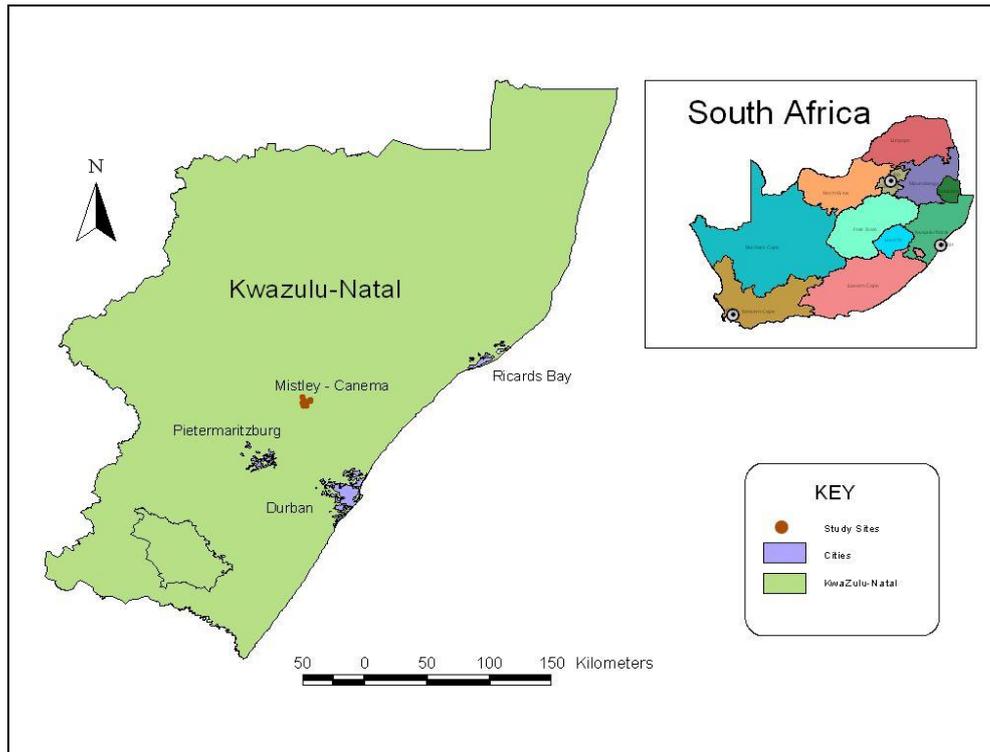
Figure 6.1   Location of Mistley-Canema Estate in the KwaZulu-Natal, South Africa.

3.2   Hyperion Hyperspectral Satellite

Hyperspectral images acquire many, very narrow, contiguous spectral bands, covering the visible, near-infrared, mid-infrared, and thermal infrared regions of the electromagnetic spectrum, allowing for the construction of an almost continuous spectrum for every pixel in the scene. The Hyperion sensor on board the EO-1 satellite was the first hyperspectral sensor to operate from space and orbits at an altitude of 705 km. This sensor has a spectral resolution of 10 nm and covers 242 bands from 380 – 2500 nm. The spatial resolution of the image is 30 m and the swath width of an image is 7.5 km. The Hyperion data used in this study were acquired on 21 July 2006 (Govender *et al*., 2007).

3.3   LAI Measurement

The LI-COR LAI-2000 plant canopy analyzer (LAI-2000, LI-COR, Inc., Lincoln, Nebraska, USA) was used to measure plantation forest LAI in each of the three tree species. Due to the height of the trees, it was not possible to take measurements above the canopy. Thus the "remote mode" method was used, i.e., two control units are used to log the above and below canopy readings respectively. At each of the four study sites (i.e. 12 year old pine, 15 year old pine, 4 year old wattle and 10 year old eucalyptus) ten sets of four reading were taken at each plot for model development and then repeated

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for model validation. Each of the points were taken at random beneath the canopy. A separate syncronised instrument was located in an open area and was taking readings every 15 seconds, representing the above canopy readings. During the data processing stage the above and below canopy readings were compared to determine the fraction of light transmitted or absorbed by the canopy. A sunlit canopy was avoided by taking readings just before sunset when the solar elevation is low (below 45°). A 45° view lens was used to restrict the view of the sensor. The models were developed by overlaying the points where the LAI readings were taken on the images that had been corrected with each of the three vegetation indices (i.e. NDVI, SAVI and Vogelmann 1). The pixel values for each point were then extracted and related to its corresponding LAI value. A linear regression model was then fitted to the data using Microsoft® Excel 2003.

3.4   Atmospheric Correction of Hyperion Image

Atmospheric correction is a pre-processing procedure that is undertaken to compensate for the effects of atmospheric particles through absorption and scattering of the radiation. The objective of performing an atmospheric correction is to retrieve the surface reflectance from the remotely sensed image by removing atmospheric effects. The conversion involved the removal of atmospheric absorptions and scattering as well as removal of the shape of the solar irradiance spectrum. Atmospheric and radiometric corrections were performed using the ENVI 4.3 remote sensing software package using the empirical line method of atmospheric correction. This method compares radiance values reflected from the surface to reflectance values measured on the ground with a calibrated hand-held spectrometer (Research Systems Inc, 2005). Using several ground truth data targets, the relationship between radiance at sensor and reflectance on the ground can be extracted. Since the effect of the atmosphere is multiplicative (by gasses) and additive (by aerosols) linearity is assumed in each wavelength (i.e. image layer) and a gain and offset are used as estimates of these atmospheric effects on radiance. After calculating these for all wavelengths, the gains and offsets could be applied to the image as a whole and the reflectance in all pixels can be estimated.

3.5   Vegetation Indices

The relation between remotely sensed measurements and vegetation parameters is captured by various vegetation indices. A vegetation index is defined as a mathematical combination of channels or bands that indicates the presence or condition of green vegetation (Lillesand and Kiefer, 1999). Much work has centered on seeking correlations between various plant canopy attributes and a variety of vegetation indices (Dye *et al*., 2002). The most commonly used vegetation indices utilize the information contained in the red and near infrared reflectances; either as ratios or differences (Dye *et al*., 2002). Live green plants absorb solar radiation in the photosynthetically active radiation (PAR)

spectral region (between 400 and 700nm), which they use as a source of energy in the process of photosynthesis. Leaf cells have also evolved to scatter (i.e. reflect and scatter) solar radiation in the near-infrared (NIR) region (700 to 1300nm) because the energy is not sufficient to synthesize organic molecules. If the plant absorbed strongly in the NIR, the result would be that the plant would overheat (Gates, 1980). Vegetation indices are routinely used to determine green biomass, green leaf area, LAI, stand biomass, percent ground cover, amount of photosynthetically active vegetation, photosynthesis activity and productivity (Baret and Guyot, 1991). Hundreds of vegetation spectral indices have been reported in the literature, but few are commonly used and have been tested in different vegetation studies. Near infrared/Red (NIR/R) spectral band ratios such as the Soil Adjusted Vegetation Index (SAVI), Eq. (6.5) and Normalized Difference Vegetation Index (NDVI), Eq. (6.8) are widely used to estimate LAI over large areas.

The SAVI is expressed as follows:

$$SAVI = \frac{(1+L)(NIR-R)}{NIR+R+L} \qquad (6.5)$$

Where L = 0.5, and is an adjustment factor to minimize the backscatter effect of soil background reflectance through the canopy.

According to Schultz and Engman (2000), LAI is related to SAVI as follows:

$$SAVI = c_1 - c_2 \, e^{-c3.LAI} \qquad (6.6)$$

Where:

$c_1 = 0.69$; $c_2 = 0.59$; $c_3 = 0.91$

Therefore:
$$LAI = \frac{-\ln(SAVI + 0.371)}{0.48} \qquad (6.7)$$

The Normalized Difference Vegetation Index (NDVI) is one of the oldest, most well known, and most frequently used VIs having been used to study vegetation and phenology since the early 1970's. The combination of its normalized difference formulation and use of the highest absorption and reflectance regions of chlorophyll make it robust over a wide range of conditions and because it minimises the effects of topography, no prior knowledge of the ground conditions are required, and it is sensitive to the photosynthetically active vegetation (McGwire *et al.*, 2000). It can, however "saturate" in dense

vegetation conditions when LAI becomes high. Saturation occurs when the vegetation index value no longer increases with an increase in biomass or LAI (Dye *et al.*, 2002). The NDVI ratio is the ratio of shortwave infrared and red reflectance. NDVI is defined by the following equation:

$$\text{NDVI} = \frac{NIR - red}{NIR + red} \qquad (6.8)$$

Another vegetation index is the Vogelmann Red Edge Index 1 (VOG1) (Vogelmann, 1993), which is a narrowband reflectance measurement that is sensitive to the combined effects of foliage chlorophyll concentration, canopy leaf area, and water content. Applications include vegetation phenology (growth) studies, precision agriculture, and vegetation productivity modelling. VOG1 is defined by the following equation:

$$\text{VOG1} = \frac{\text{Reflectance at } 740nm}{\text{Reflectance at } 720nm} \qquad (6.9)$$

Narrowband greenness VIs are a combination of reflectance measurements sensitive to the combined effects of foliage chlorophyll concentration, canopy leaf area, foliage clumping, and canopy architecture. Narrowband greenness VIs are designed to provide a measure of the overall amount and quality of photosynthetic material in vegetation, which is essential for understanding the state of vegetation. These VIs use reflectance measurements in the red and near-infrared regions to sample the 'red edge' portion of the reflectance curve. The 'red edge' is a term used to describe the steeply sloped region of the vegetation reflectance curve between 690 nm and 740 nm that is caused by the transition from chlorophyll absorption and near-infrared leaf scattering. Use of near-infrared measurements, with much greater penetration depth through the canopy than red measurements, allows estimation of the total amount of green material in the column (RSI, 2005).

Narrowband greenness VIs are more sophisticated measures of general quantity and vigor of green vegetation than the broadband greenness VIs. Making narrowband measurements in the red edge allows these indices to be more sensitive to smaller changes in vegetation health than the broadband greenness VIs, particularly in conditions of dense vegetation where the broadband measures can saturate. Narrowband greenness VIs are intended for use with high spectral resolution imaging data, such as that acquired by hyperspectral sensors (RSI, 2005).

3.6 Accuracy Assessment

To evaluate how well the estimated values obtained from the remotely sensed data compared to the observed data measured using the LI-COR LAI canopy analyser, the Root Mean Squared Error (RMSE) (Equation 6.10) statistic was used. The closer the RMSE is to zero, the better the result.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(E_{ij} - O_j\right)^2} \qquad (6.10)$$

Where E is the estimated value, O is the observed value, and n is the number of samples.

4. RESULTS

The LAI values were measured on the 21 June 2007 using the LI-COR LAI- 2000 canopy analyzer as described in Section. 3.3. These were used to develop the relationships with the three vegetation indices and are shown in Table 6.1.

Table 6.1   LAI measurements taken with the LI-COR LAI 2000 canopy analyzer in four commercial forest stands at Mistley-Canema on 21 June 2007 at 04:30 pm on a clear and sunny day, used for model validation.

Pine 12year	Pine 15year	Wattle 4year	Eucalyptus 10year
2.62	3.61	2.89	1.98
2.72	3.67	2.92	2.13
2.84	3.76	3.00	2.29
2.89	3.80	3.41	2.36
2.93	3.85	3.46	2.65
2.94	3.90	3.60	3.01
2.99	3.99	3.62	3.95
3.02	3.79	3.89	2.62
3.22	3.81	3.94	2.71
3.26	3.76	4.19	2.53

The relationships established between the measured LAI of all the sampled species and the three vegetation indices used are shown in Figures 6.2 to 6.4.
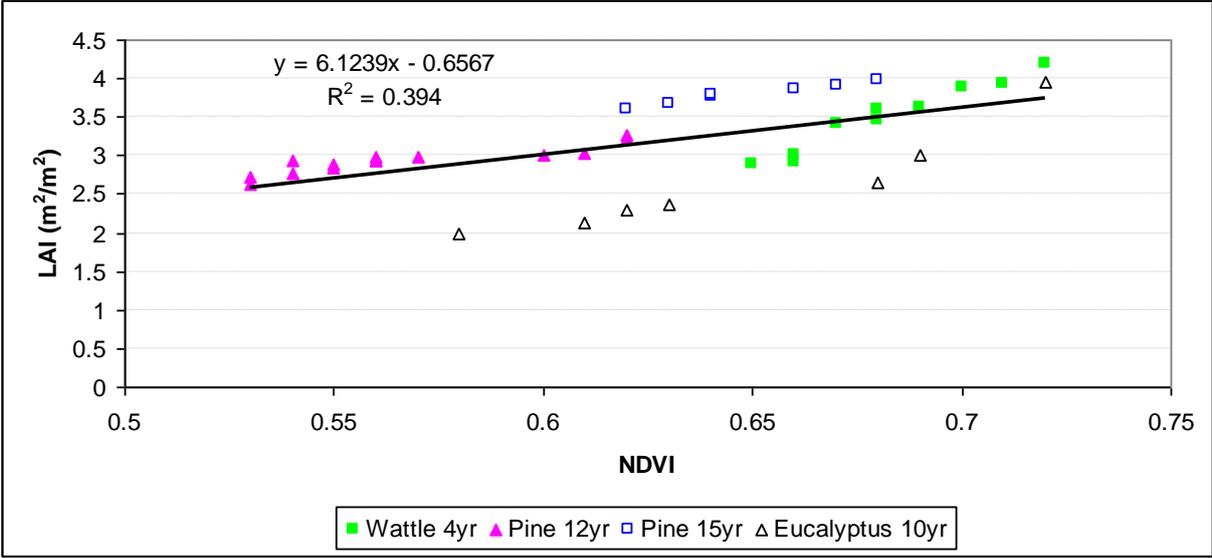
Figure 6.2   Relationship between observed LAI and NDVI at Mistley-Canema Estate on 21 June 2007.

From Figure 6.2 it can be seen that the Pine 12yr and the Wattle 4yr can be estimated well when using the NDVI. The LAI of Pine 15 will be underestimated and Eucalyptus 10yr will be overestimated using the regression model obtained.
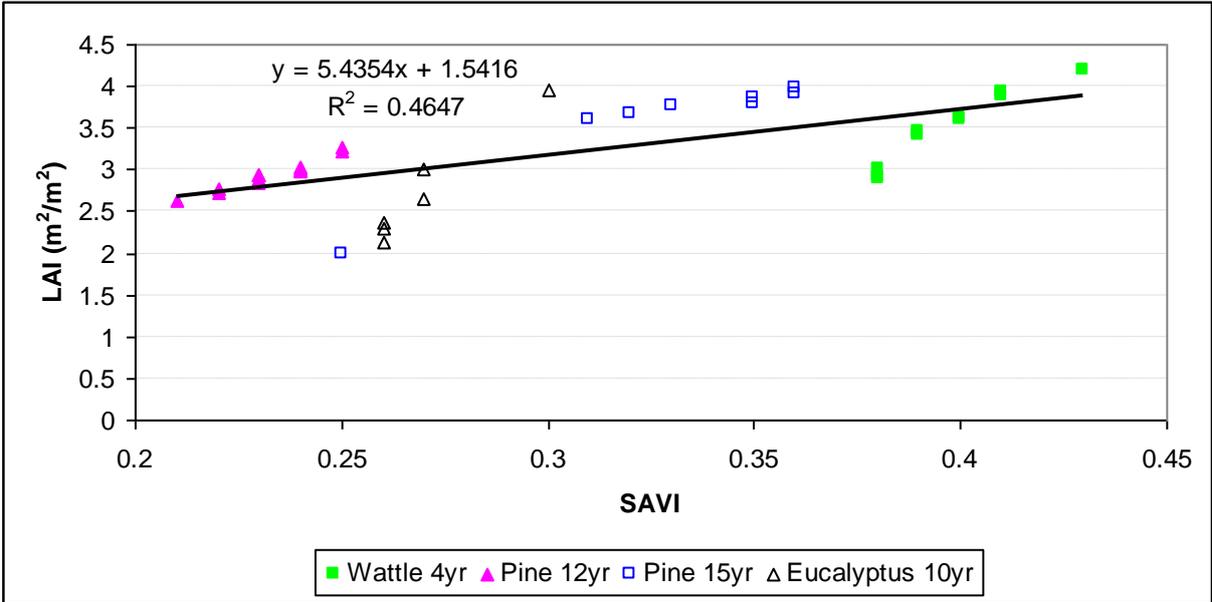
Figure 6.3   Relationship between observed LAI and SAVI at Mistley-Canema Estate on 21 June 2007.

From Figure 6.3 it can be observed that Pine 12 can be fairly well estimated, but the other species are scattered both above and below the regression model.
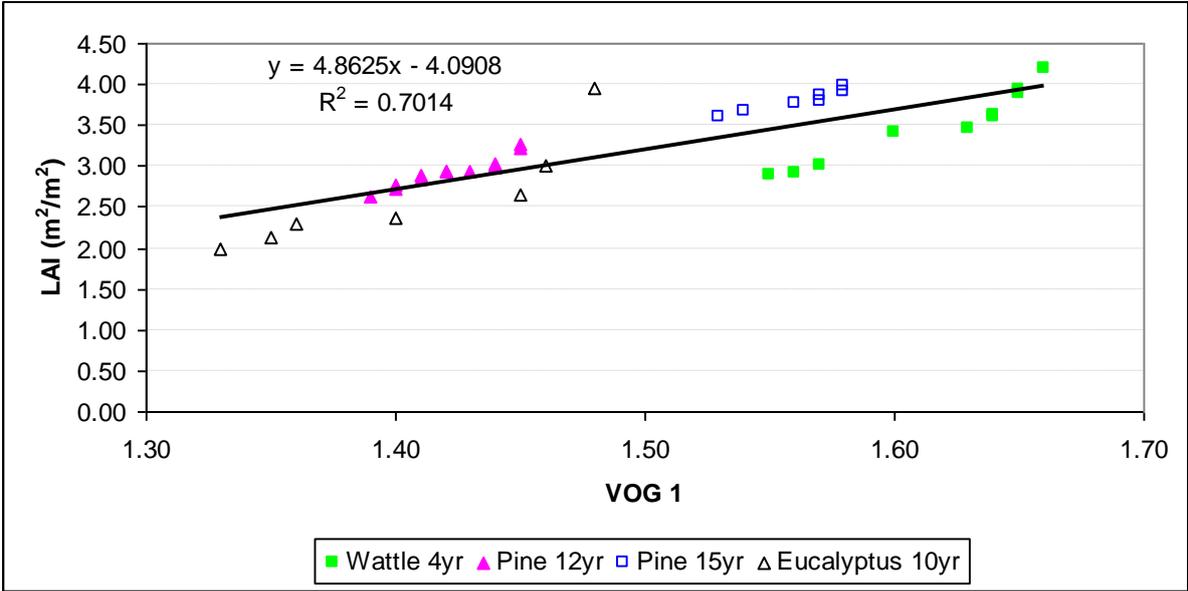
Figure 6.4   Relationship between observed LAI and the Vogelmann Index 1 at Mistley-Canema Estate on 21 June 2007.

Figure 6.4 shows that the LAI of all species can be estimated with a fair degree of accuracy using the Vogelmann index 1. Pine 12 shows the best correlation with the regression model.

Table 6.2   Accuracy assessment results obtained for the three vegetation indices

VEGETATION INDEX	R^2	RMSE
NDVI	0.39	0.43
SAVI	0.46	0.41
VOG 1	0.70	0.30

Based on the analyses above, of the three vegetation indices used in this study, the Vogelmann index 1, was the most successful for estimating the LAI for all species. The R^2 and the RMSE values as shown in Table 6.2, for each of the three vegetation indices used, confirm that the Vogelmann index 1 is the most suitable index to use for the estimation of LAI in this case study. The Vogelmann index 1 performed better than the NDVI and SAVI because it is a narrowband index as opposed to a broadband index. The NDVI and SAVI are susceptible to saturating in dense vegetation. This saturation occurs when the vegetation index no longer increases significantly with an increase in biomass or LAI as can be seen when using the SAVI for wattle 4yr and eucalyptus 10yr where the slope of the of the data points increases steeper than the trendline. The narrowband VOG 1 index

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penetrates deeper through the canopy and allows for better estimations of biomass or LAI in denser vegetation. A comparison of the estimated and observed LAI values for each land use are shown in Fig. 6.5
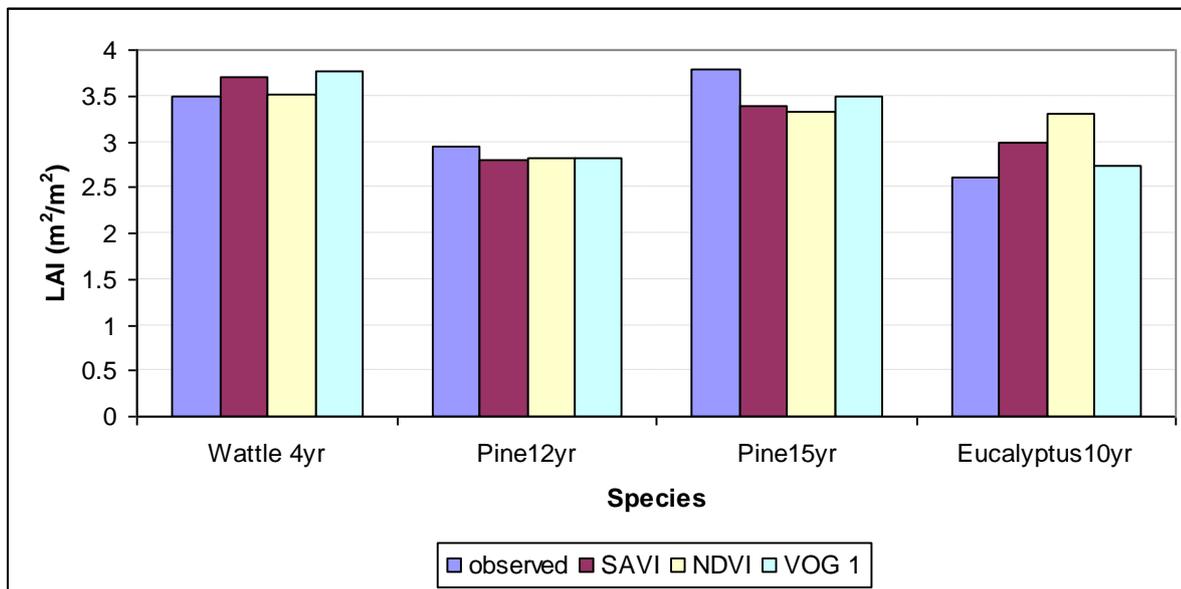
Figure 6.5   Average LAI estimated using three different vegetation indices.

Figure 6.5 shows that the average estimated LAI values correspond well with the observed values. Using this information, the data obtained from the Hyperion image can be converted into an image of LAI for the study area as shown in Figure 6.6, which has been performed using the Vogelmann index 1. Furthermore, the image that has been created for the LAI (Figure 6.6) can be used to estimate the maximum storage capacity as shown in Figure 6.7, by applying the von Hoyningen-Huene (1981) equation (Equation 6.1). Similarly, the daily interception could be estimated if the daily rainfall was known by using Equation 6.4, described in Section 2.

Figure 6.7 represents the maximum storage capacity for the same classes (i.e. using the same LAI values) as represented in Figure 6.6.
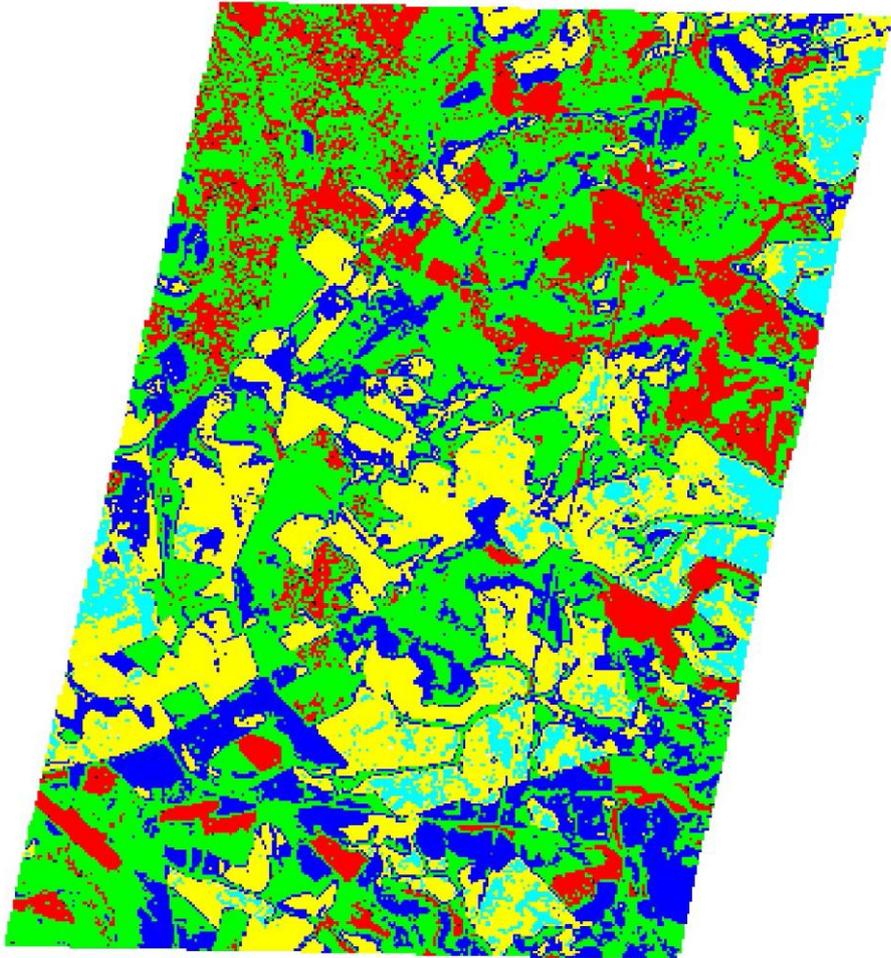
Figure 6.6   The LAI distribution over the Mistley-Canema Estate using the Vogelmann index 1 on
               21 June 2007.
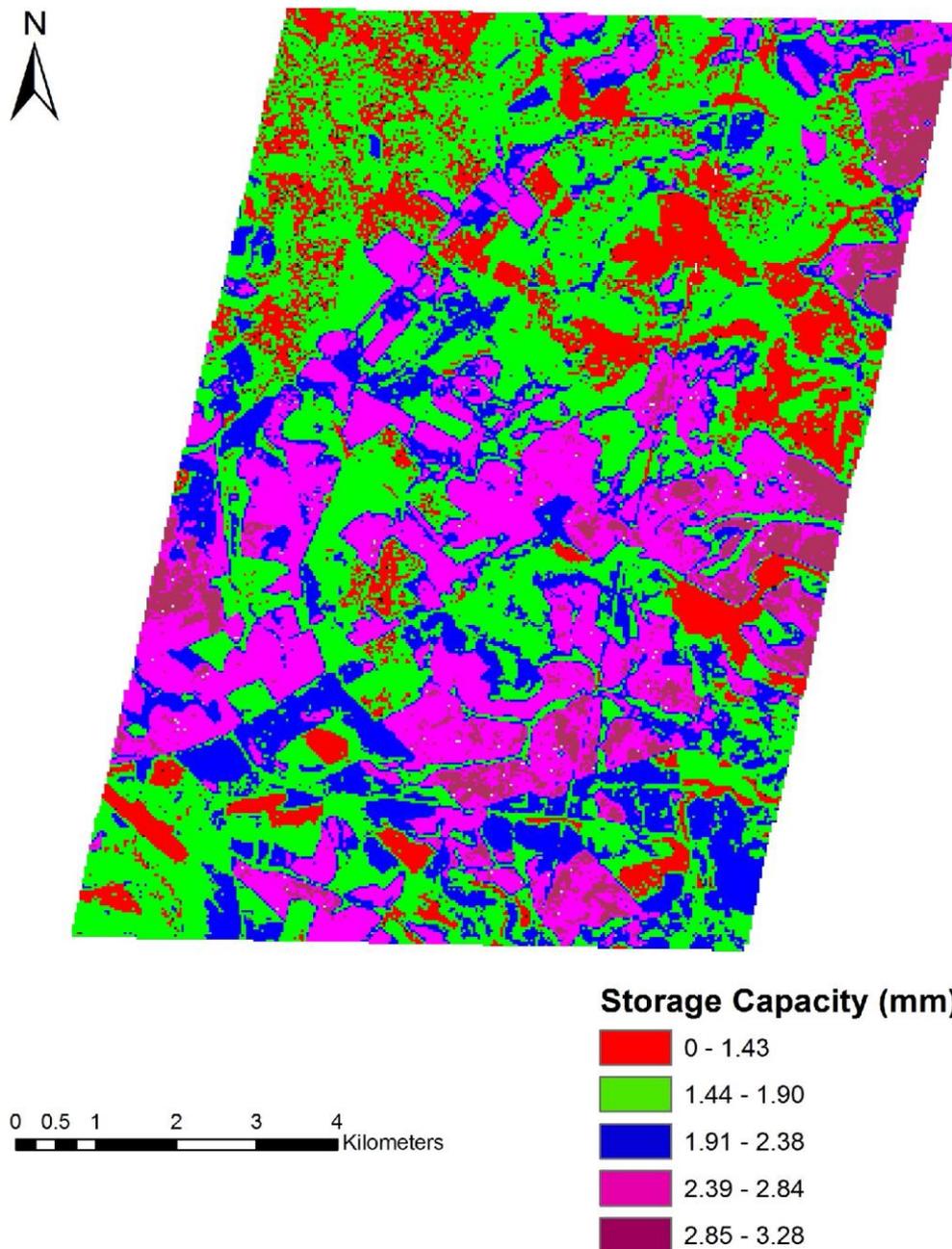
Figure 6.7   The maximum storage capacity over the Mistley-Canema Estate using the Vogelmann index 1 on 21 June 2007.

5.   DISCUSSION AND CONCLUSION

Field based methods of estimating LAI and biomass of forestry plantations are expensive and time consuming. Remotely sensed LAI values provide a means of gaining spatial information about various plant biophysical attributes that can be used in hydrological and process based growth models and can be determined relatively cheaply and easily using satellite imagery (Megown *et al.*, 2000). The ability to remotely predict LAI and eventually water use over a large area is sought after by various stakeholders and the forestry industry, as well as water resources managers and planners. Due to the future availability and accessibility of hyperspectral sensors in southern Africa there should be an increased interest in using high spectral resolution data for a wide variety of environmental applications

There has however been a reluctance to use remote sensing for hydrological applications by the hydrology community at large and in southern Africa in particular. This can be attributed to reasons such as, the unavailability to the relevant hardware and software, lack of knowledge of the application of remote sensing techniques and the reluctance to change conventional and well established methods (Shultz and Engman, 2002). Now in its 4th decade, the use of earth observation data in water resources s however becoming increasingly popular and has been used by researchers such as Dye *et al.*, (2002), Ghebremicael *et al.*, (2004), Sprintsin *et al.*, (2007), Kongo and Jewitt (2007), to mention but a few.

The results obtained from this study show that the use of remote sensing for the estimation of LAI is possible with a relatively high degree of accuracy. The potential to use remote sensing to estimate LAI on a large scale and link this to water resources studies at various scales is just one possible application. For example, with this data, the canopy interception can be estimated using the equations described in Sect. 2 and represented visually to obtain a better understanding of the spatial variability of canopy interception or maximum storage capacity, as shown in Fig. 6.7. The methodology used in this study is repeatable elsewhere, but the models developed are site and image specific and should not be used elsewhere. This is because the reflectance values would vary in different images depending on which satellite was used to acquire the image and how the image was corrected. In this study only one image was used to develop a method of estimating LAI, canopy interception and canopy storage capacity. These values are likely to change from season to season, and therefore the values obtained in this paper should be used with caution and bearing this in mind. However, the methodology used in this paper is transferable to many other satellite images and is not dependant on the time of year. If the temporal variation is required, there are number of satellites that provide freely available data at a high temporal resolution such as MODIS which has a temporal resolution of 8 days. However, there is a compromise on the spatial resolution with these images which have a spatial resolution of between 250 m and 1000 m.

It can be concluded from this study that remote sensing is a valuable tool for the estimation of LAI for applications in hydrology, such as modelling canopy interception. With a limited amounted of field work, LAI measurements can be utilised at large spatial scales, and with the launch of southern African satellites, data availability should improve (SunSpace, 2011). Although remote sensing may reduce the amount of field work needed, it cannot be excluded completely without a detrimental impact and high levels of uncertainty on the outcome of the task. It is important to accurately estimate LAI as Xiao *et al*., (1998) found that modelling canopy interception was most sensitive to storage capacity and LAI as the storage capacity is directly related to the LAI. Similarly, Limousin *et al*., (2008) found that a 25% reduction in storage capacity reduces interception loss by 8.6%

The most robust vegetation index in this study was found to be the Vogelmann index 1 having an R^2 value of 0.7 and RMSE of 0.3. The Vogelmann index 1 was developed to be used with high spectral resolution data such as the hyperspectral data used in this study and justifies the good results obtained. Also, the Vogelmann index 1 performed better than the NDVI and SAVI because it is a narrowband index as apposed to a broadband index. NDVI and SAVI are susceptible to saturation in dense vegetation. This saturation occurs when the vegetation index no longer increases significantly with an increase in biomass or LAI. This can be seen when using the SAVI for wattle 4yr and eucalyptus 10yr where the slope of the of the data points increases steeper than the trendline. The narrowband VOG 1 index penetrates deeper through the canopy and allows for better estimations of biomass or LAI in denser vegetation. The SAVI and NDVI had R^2 values of 0.46 and 0.39, and RMSE of 0.43 and 0.41 respectively. However, the SAVI and NDVI were able to be used to estimate certain species accurately. For example, NDVI can be used to estimate the LAI of 12 year old *Pinus patula* and 4 year old wattle accurately, even though it is not as robust for all species as the Vogelmann index 1. Although the SAVI and NDVI might not have produced results that are as good as the Vogelmann index 1, it can be seen from Figure 5 that the difference between the observed and predicted values using the SAVI and NDVI are acceptable and suitable to use in the estimation of canopy interception. Although the results obtained in this study indicate that remote sensing techniques can be used in interception studies, further fieldwork to verify the model is needed. Such field work on interception at compartment scale as well as national scale are ongoing, and form a second complementary phase to this study.

Acknowledgements

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CHAPTER 7

An investigation into the impact of climate change on canopy interception and transpiration in commercial forests in South Africa

An investigation into the impact of climate change on canopy interception and transpiration in commercial forests in South Africa

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ABSTRACT

Forests are critically influenced by climate as their growth depends on photosynthesis, which requires resources such as light, water and atmospheric CO_2. Of concern currently is the rate and magnitude at which global warming has taken place over the past few decades. This has been observed in measurements of, *inter alia*, atmospheric CO_2 concentrations and in global temperature records. There is however still apprehension about climate change and the many uncertainties that surround it imply that its full impacts are, to date, still inadequately understood. Possible effects on plants due to rising atmospheric CO_2 concentrations could include reductions in transpiration, an increase in leaf area index (LAI) and therefore a change in canopy interception. To investigate the possible impact of climate change on forestry and site water balance in South Africa the CABALA model was used to model LAI and transpiration of *Eucalyptus grandis* and *Pinus patula* under 9 different climate change scenarios, including changes in temperature, rainfall and atmospheric CO_2. LAI results from the model were then used to model canopy interception. Results show that LAI may increase by as much as 24% and transpiration may decrease by as much as 13%, depending on the scenario, location and tree species. However, under these scenarios, it was found that canopy interception does not change greatly, leading to the conclusion that under climate change conditions, canopy interception may not become a more dominant component of the hydrological cycle than it currently is, but the results show that it remains an important consideration for water resources management.

1. INTRODUCTION

Forests are inextricably influenced by climate (Kirschbaum, 2000) as their growth and location depends on photosynthesis, which requires climate dependant resources such as light, water and atmospheric carbon dioxide (CO_2). Thus, solar radiation, temperature, CO_2 and rainfall determine the location and rate of growth of forests. There has recently been much attention given to global warming

and modern climate change (Dollar and Goudie, 2000). However, climate change is as old as the atmosphere itself, and that climates have changed radically in the past is indisputable (Tyson and Preston-Whyte, 2000). Of concern currently is the rate and magnitude at which global warming has taken place over the past few decades (Warburton and Schulze, 2008). While there have been many studies on how plants will respond to changes in rising atmospheric CO_2 concentrations, there are few that include the possible changes in temperature and rainfall as well.

Over the past few decades, the phenomenon of climate change has occurred and will continue to do so more rapidly than has been recorded in geological history (Levine, 1992). This has been observed in measurements of, *inter alia*, atmospheric CO_2 concentrations increasing by approximately 35% from 280 parts per million (ppm) since the dawn of the Industrial Revolution to approximately 380 ppm at present, and also in global temperature records, with global mean surface air temperatures having increased by between 0.2 and 0.6 °C since the late 19th century (IPCC, 2001; 2007). Annually, industry adds approximately 6.3 gigatonnes of carbon as CO_2 to the atmosphere and the destruction of forests adds an additional gigatonne of CO_2 annually. There is however still apprehension about climate change and the many uncertainties that surround it imply that its full impacts are, to date, still inadequately understood (IPCC, 2007). Major concerns surround the concept of increasing temperatures and associated shifts in precipitation attributes and patterns, which are likely to result in significant changes in water quantity and quality (Schulze *et al*., 2005b). Precipitation changes are more spatially variable than the projected temperature changes. Although a general increase in precipitation is expected, some regions such as the south western Cape of South Africa are predicted to see a reduction in the future (Schulze, 2010). There are two main reasons for the uncertainty in precipitation prediction. The first is that precipitation is a secondary process in General Circulation Models (GCMs) and, as such, is poorly represented; and secondly, heavy precipitation systems frequently occur on scales that are considerably smaller than the typical grid scale of GCMs, which is two or three degrees of latitude/longitude. Despite these uncertainties the evidence for potential large scale climatic change is now sufficiently strong to justify further investigations not only of the causes, but particularly of its consequences in a variety of environments (Melack, 1992). Thus, studies on how forest plantations and natural forests can be expected to respond to climate change both structurally and in terms of water use efficiency are needed.

The primary effects on plants due to rising atmospheric CO_2 concentrations have been well documented and include reductions in stomatal conductance and transpiration, improved water use efficiency, higher rates of photosysnthesis, and increased light-use efficiency (Ainsworth and Long, 2005). A transpirational suppression per unit leaf area does not necessarily imply that the total transpiration over the growing season decreases automatically with increasing CO_2. The total transpiration rate depends on how much the expected increase in leaf area index (LAI) balances out

the decrease in transpiration rate (Schulze, 1995; Kirschbaum, 2000). However, a major challenge that scientists are faced with today is the need for predictions of plant responses to climate change, that are based on sound theoretical understanding and supported by experimental evidence and so boost confidence in model output. This need is particularly important for trees, because forests dominate the terrestrial biosphere, in terms of both carbon stocks and fluxes. Such studies are especially difficult for trees, because of the long lifespans of many species make it impossible to document the long-term effect of CO_2 enrichment above present day levels and any adaptations that may occur. This makes long-term forecasting of tree growth and gas exchange heavily dependent on assumptions about the character of adaptive growth regulation (Buckley, 2008). From the findings of many Free-Air CO_2 Enrichment (FACE) experiments, it is generally accepted that there will be an increase in LAI with an increase in atmospheric CO_2 (Ainsworth and Long, 2005). With an increase in LAI, trees will potentially have a greater canopy storage capacity than they currently do, meaning that canopy interception may increase. Thus, an important question is, with changes in atmospheric CO_2, temperature, and rainfall, how will LAI and hence canopy interception change? This is an important question to answer, as interception is an important process both hydrologically and in terms of water resources management.

The aims of this study are therefore:
1. To briefly review FACE experiments to add context to the importance of this study.
2. To simulate changes in LAI and transpiration under different scenarios of climate change using the CABALA model, and
3. Use the simulated LAI results as an input into the "variable storage Gash model" to model canopy interception under plausible scenarios of climate change.

2. FREE-AIR CO_2 ENRICHMENT (FACE) EXPERIMENTS

The primary effects and conclusions regarding the response of plants to rising atmospheric CO_2 have come from studies of individual species grown in controlled environments or enclosures. While the conclusions drawn from these experiments form the basis of plant physiological responses to elevated atmospheric CO_2, there are limitations to using enclosure systems (Ainsworth and Long, 2005). Enclosures may amplify "downregulation" of photosynthesis and production (Morgan *et al*., 2001), and may through environmental modification produce a "chamber effect" that exceeds the effects of the elevated CO_2 concentration.

In contrast, FACE experiments allow the exposure of plants to elevated CO_2 under natural and fully open-air conditions. FACE technology uses no confinement structures, but rather an array of vertical and horizontal vent pipes to release jets of CO_2 enriched air or pure CO_2 gas at the periphery of the vegetation plots. FACE relies on natural wind and diffusion to disperse the CO_2 across the

experimental area. Early FACE systems utilized blowers or fans to inject CO_2 enriched air into the treatment area, but more recent studies have employed a FACE technology in which pure CO_2 gas is released as high velocity jets from emission tubes positioned horizontally at the periphery of a FACE octagon as illustrated in Figure 7.1. FACE design allows for good spatial and temporal control of CO_2 concentrations throughout crop canopies and also relatively young homogeneous forest plantations (Ainsworth and Long, 2005).
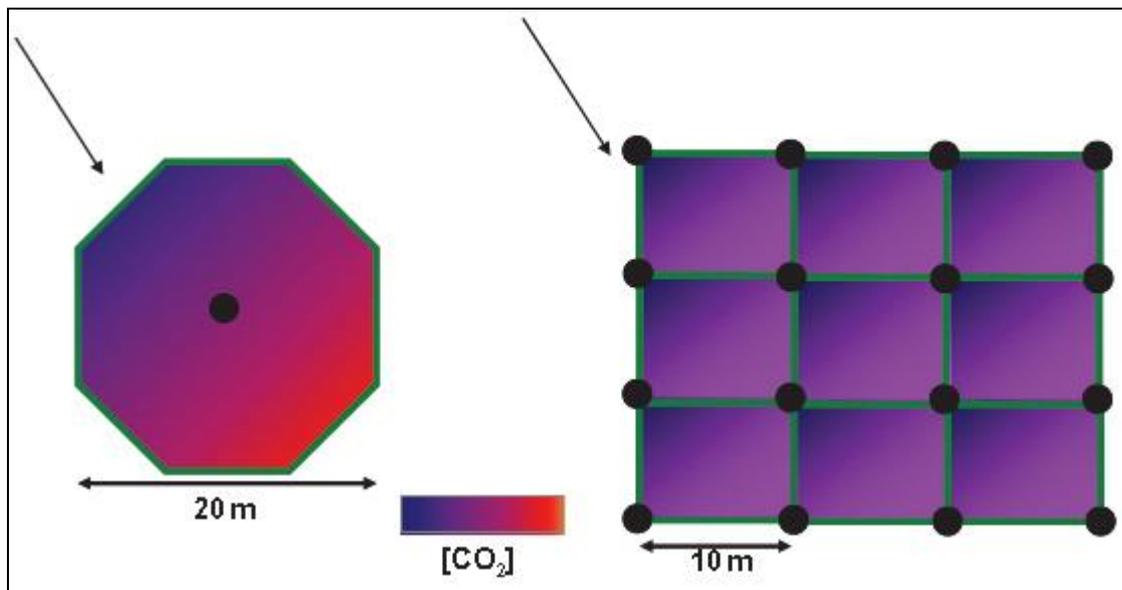
Figure 7.1   A typical distribution of CO_2 across a free air CO_2 enrichment (FACE) octagonal plot or a hypothetical gridded FACE system. The arrows indicate the direction of the wind, and the colour scale indicates the gradient in CO_2 across a plot. The black circle indicates the location of a control box with a CO_2 analyser, anemometer and CO_2 regulator. The green lines represent pipes for the release of CO_2 (From: Ainsworth *et al*., (2008))

2.1   A Review of FACE Experiments: Ainsworth and Long (2005)

A comprehensive review based on 15 years of FACE experiment data was presented by Ainsworth and Long (2005). Their review was based on data from 124 peer review manuscripts that analysed more than 40 plant species from 12 FACE sites shown in Table 7.1, with CO_2 enrichment ranging between 475 and 600 ppm. Their findings show that under these conditions, trees may increase LAI by 21%, while, herbaceous C3 grasses showed no significant change in LAI (Ainsworth and Long, 2005). The reported LAI responses of trees to elevated atmospheric CO_2 are variable, with larger responses typically found for young trees in open stands, or for mature stands with lower LAI. Buckley (2008) suggests that there is little to no response in mature forests with high LAI. However, no FACE studies of the species being considered in this study could be found i.e. *E. grandis and P. patula*.

Table 7.1   Large scale FACE facilities reviewed by Ainsworth and Long (2005).

FACE site	Location	Elevated [CO2] (ppm)	Ecosystem	First year of exposure
Aspen FACE FACTS 2	Rhinelander, WI, USA	Ambient +200	Aspen forest	1998
BioCON	Cedar Creek, MN, USA	550	Natural prairie grassland	1998
ETH-Z FACE Swiss FACE	Eschikon, Switzerland	600	Managed grassland	1993
FACTS 1 Duke Forest	Orange County, NC, USA	Ambient +200	Loblolly pine forest	1996
Maricopa FACE	Maricopa, AZ, USA	550 Ambient +200	Agronomic C3 and C4 crops	1989
Nevada Desert	Mojave Desert, NV, USA	550	Desert ecosystem	1997
Oak Ridge	Roane County, TN, USA	Ambient +200	Sweetgum plantation	1998
Pasture FACE	Bulls, New Zealand	475	Managed pasture	1997
POPFACE	Viterbo, Italy	Ambient +200	Poplar plantation	1999
Rapolano Mid FACE	Chianti Region, Italy	560-600	*Vitis vinifera* (grape) *Solanum tuberosum* (potatoe)	1995
Rice FACE	Shizukuishi town, Japan	Ambient +200	*Oryza sativa* (rice)	1998
SoyFace	Champaign, IL, USA	550	*Glycine max* (Soybean) *Zea mays* (maize)	2000
OzFACE	Australia	550	*Themeda triandra* (grass)	2001

3.   METHODOLOGY

The methodology used to determine LAI and transpiration under climate change scenarios is described in the subsequent sections. The simulated LAI together with climatic data is then used to model canopy interception using the variable storage Gash model. A schematic of the methodology is illustrated in Figure 7.2.
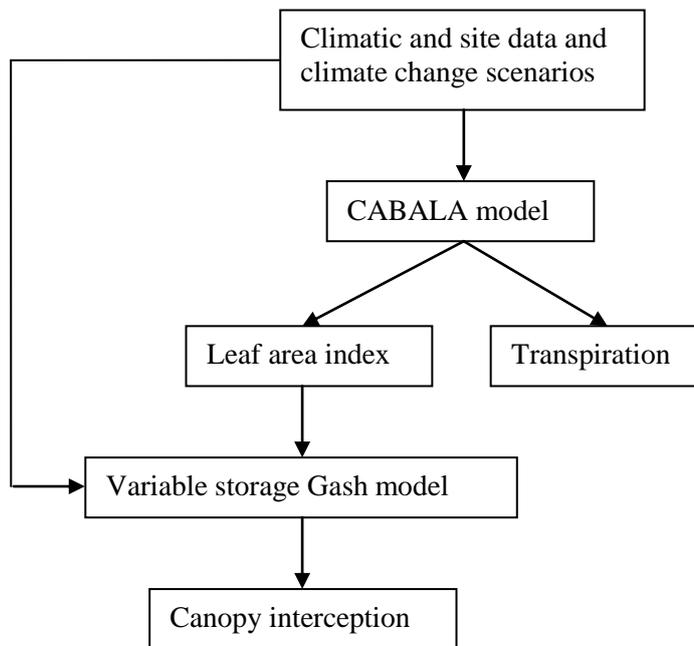
Figure 7.2   Schematic of the methodology undertaken in the study.

3.1   CABALA (CArbon BALAnce) Model

The CABALA model was chosen to simulate LAI and transpiration, because it is able to predict forest growth under climate change scenarios. CABALA (Battaglia *et al*., 2004) is a detailed tree physiology model and predicts stand development, water use and soil and stand nutrient dynamics on a daily time scale in response to climatic factors, soil water and nutrient availability, and to silvicultural options such as fertilisation, thinning or pruning. It has detailed multi-layered soil water balance and nutrient cycling submodels. However, this generality comes at a cost: CABALA is numerically intensive, far more so than other well known tree physiology models, such as 3-PG (Landsberg and Waring, 1997) or the PROMOD hybrid model.

Much of the model draws on, and combines existing concepts and submodels of leaf, tree and stand growth that have been well validated themselves. For example, the submodel used in PROMOD

(Battaglia and Sands, 1997) to predict canopy photosynthesis is coupled with a model of stomatal conductance to develop a fully coupled photosynthesis water-use submodel in CABALA. CABALA includes a detailed submodel of biomass partitioning that takes into account the structure of the trees and the availability of light, water and nutrients, and distributes new biomass so as to maintain balanced and coordinated growth with a minimum partitioning to woody tissues consistent with the need for structural support. CABALA is parameterized largely from the results of physiological experiments and the agreement between its predictions and observed stand growth has been remarkably good under a wide range of conditions and silvicultural regimes (Sands, 2003).

3.1.1 Verification of the CABALA model

The CABALA model has been verified under a wide range of conditions in Australia (Sands, 2003; Battaglia *et al*., 2004). Battaglia *et al*., (2004) describe the model verification at four different sites in Australia. The first site is a rainfall gradient in south-western Western Australia and the second is an altitude gradient in southern Tasmania. The third site in northern Tasmania covers a number of sites with a wide range of soil fertility and conditions. The fourth site was a spacing trial in Western Australia. In all cases, the model accurately predicted LAI, biomass partitioning between the stem, branches and foliage, as well as stress effects. The CABALA model has also been used in a climate change vulnerability and adaptation study in Australia (Battaglia *et al*., 2009).

3.1.2 Basis for the selection of the CABALA model

Few models which predict forest stand response to climate variation exist. In the context of a South African study, it was necessary to consider commercial forest species (*i.e. Pinus* and *Eucalyptus*) that contribute the bulk of South Africa's commercial forests in order to assess the potential of a changing climate on interception and its likely impact on the countries water resources. The CABALA model (Battaglia *et al*., 2004) met these criteria and was selected for the following reasons:

- It has a photosynthetic model that, while simple, is amenable to inclusion of CO_2 effects and will capture the interactions between vapour pressure deficit (VPD), CO_2 concentration, water stress and nutrient supply. Daily gross primary production is calculated by coupling uptake of carbon and transpiration of water through stomatal aperture via the Ball-Berry equation (Ball *et al*., 1987). Daily gross photosynthetic production and canopy conductance are then summed from calculations made at half daily intervals using average morning and afternoon temperature, incident radiation, partial pressure of CO_2 and vapour pressure deficit (after Sands, 1995). These daily values are used in the daily time-step component of the rest of the model.

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- Both temperature and respiration respond and acclimate to temperature changes. Both of these traits are important for modelling plants in changing environments; failure to include acclimation may over-estimate respiration as climates warm and lead to under-estimation of photosynthetic production as temperatures move away from optimal temperatures (Battaglia *et al.*, 1997).

- It offers the potential for allocation of woody tissue to respond to changes in supply of resources for growth. Changes in allocation of woody tissue have been observed in FACE experiments where there has been an increase in below-ground allocation such that proportional increases in tree volume production are less than proportional changes in NPP, particularly when fertility is low (e.g. Norby *et al.*, 2003).

- In addition to the effects of resource supply (light, water, nutrients) on growth, the model captures the effects of some stress factors such as frost, photoinhibition and loss of hydraulic conductivity associated with drought. Current limits to plantation development and the selection of species are controlled by survival and risk of damage as well as average production. These limits will change under climate change and need to be explored.

- The model allows for silvicultural management scenarios around spacing at planting, fertilisation and thinning to be developed and the implications of these to be explored. Realistic inclusion of these aspects is vital if management based adaptation options are to be explored.

- The model runs on a daily time step. This allows exploration of drought risk, changes in maximum and minimum temperature shifts to be explored and shifts in seasonal rainfall patterns.

- The model generates LAI as an output, which is necessary for modelling canopy interception.

3.1.3 Approach to simulation of leaf area index

Predicting the LAI of a forest stand is a complex process (Battaglia, 2010, pers. Comm.). The CABALA model predicts LAI as follows, as described by Battaglia *et al*., (1998) and Battaglia *et al*., (2004):

The annual net photosynthetic production (biomass) of a forest stand, G (kg. C. m^{-2}. year^{-1}), can be represented as (McMurtie and Wolf, 1983):

$$G = \varepsilon Q(1 - e^{-k.LAI}) - R, \qquad (7.1)$$

Where:

ε -   is the light utilisation efficiency (kg.C.MJ^{-1}),

Q   -   is the incident photosynthetically active radiation (MJ.m^{-2}.year^{-1}),

k   -   is the canopy light extinction coefficient,

LAI   -   is the leaf area index, and

R   -   is annual respiration (kg.C. m^{-2}.year^{-1}).

However, according to Penning de Vries (1975), construction respiration is proportional to the biomass produced, and therefore Eq. 7.1 can be rewritten as:

$$G = \frac{[\varepsilon Q(1-e^{-k..LAI}) - R_m]}{1 + r_c} \qquad (7.2)$$

Where:

r_c -   is the carbon used as a proportion of dry matter produced, and

R_m -   is the maintenance respiration cost of the plant.

Following the analysis of Dewar (1996), a relationship between maintenance respiration and tissue nitrogen content exists and can be considered approximately linear. Battaglia *et al*., (1998) focussed on the changes in G and LAI, and therefore simplified the analysis by considering in detail the foliage maintenance respiration of the canopy and treating the residual plant maintenance respiration, R_{w+r}, as independent of canopy size. The total canopy carbon loss is retained as a foliage respiration rate that is dependent on crown nitrogen content and a litterfall term. Thus from Eq. 7.2, a new Eq. 7.3 can be derived as follows:

$$G = \frac{[\,\varepsilon Q(1 - e^{-k..LAI}) - r_0 n_c - \gamma.LAI/s - R_{w+r}\,]}{1 + r_c} \qquad (7.3)$$

Where:

r_0 -   is the maintenance respiration rate per unit canopy N (kg.C.kg^{-1}.year^{-1}),

n_c -   is canopy N content (kg.N.m^{-2} ground),

s -   is specific leaf area (m^{2}.kg^{-1}.DM), and

γ -   is the rate of carbon loss due to litterfall (kg.C.kg^{-1}.DM.year^{-1}).

Because the total canopy nitrogen content at the stand level is the product of average leaf nitrogen concentration, N_F, and foliage weight, Eq.7.3 becomes:

$$G = \frac{[\,\varepsilon Q(1 - e^{-k..LAI}) - r_0 N_F - \gamma.LAI/s - R_{w+r}\,]}{1 + r_c} \qquad (7.4)$$

Then, differentiating G in Eq. 7.4, and setting dG/dLAI to zero gives a target or optimum LAI:

$$LAI \quad = \quad \frac{1}{k}\ln\left(\frac{s\varepsilon Qk}{r_0 N_F + \gamma}\right) \qquad (7.5)$$

The value of LAI predicted by the model represents the "target" LAI for trees growing under particular conditions, and not necessarily the LAI that occurs on that day. This "target" is based on the assumptions that (1) there has been natural selection for trees that allocate biomass to maximize dry matter production, and (2) that there is a linear relationship between canopy respiration and foliage mass (Battaglia *et al*., 1998).

A detailed description of how the CABALA model calculates LAI can be found in Battaglia *et al*., (1998) and Battaglia *et al*., (2004). In summary, on any given day a "target" LAI is calculated which is set by the self pruning height (carbon balance point in crown) as per Battaglia *et al*., (1998). To reach this "target" LAI, the model will seek to allocate carbon and nitrogen to foliage to achieve this target, but this must be commensurate with maintaining an above to below ground biomass ratio for support and adding the additional sapwood biomass necessary to support the additional leaf area. This ratio will change if drought reduces the hydraulic conductivity of sapwood. In addition, there must be sufficient nitrogen to build new tissue – this can come from uptake or from retranslocation from senescing foliage or by reducing the nitrogen content of other leaves (down to a lower limit).

3.2 Variable Storage Gash Model

The "variable storage Gash model" is based on the models of Gash (1979) and Gash *et al*., (1995) and a full detailed description can be found in Chapter 4. The "variable storage Gash model" is based on three main assumptions:

1) The rainfall distribution pattern may be represented as a succession of discrete storms, separated by sufficiently long periods to allow the canopy and trunks to dry (Gash, 1979, Gash *et al*., 1995);

2) The rainfall and evaporation rates are constant during each storm and may be considered as constant between several storms during the same period (Gash, 1979, Gash *et al*., 1995); and

3) The maximum canopy storage capacity (S_c^{max}) is linearly related to LAI (van Dijk and Bruinzeel, 2001a, 2001b), but the storage capacity (S_c) varies with different rainfall intensites (R).

To incorporate the dependence of *q* on both drop volume and therefore kinetic energy into the model, a vegetation/species specific parameter is introduced, termed the maximum elemental volume (v_e^{max}) and is expressed in Equation 7.6. This is calculated by considering drops impacting the surface with a kinetic energy as close to zero as possible, which according to Calder *et al*., (1995) are events with an intensity of less than 0.36 mm.h^{-1}. The v_e^{max} values used in this study are as follows:

- *Eucalyptus grandis* = 0.24
- *Pinus patula* = 0.51

$$v_e^{max} = q.v_0 \text{ (i.e. } q = \frac{v_e^{max}}{v_0} \text{)} \tag{7.6}$$

where:

q   -   drop retention

v_e^{max} -   is the maximum volume of water retained by a canopy element (mm^3), and

v_0 -   is the mean volume of the rain drop (mm^3) with almost zero kinetic energy.

The term maximum storage capacity (S_c^{max}) which is obtained when the canopy is wetted with drops of almost "zero" kinetic energy and is defined as:

$$S_c^{max} = v_e^{max}.\text{LAI} = q.v_0.\text{LAI} \tag{7.7}$$

The storage capacity (S_c) for non-zero kinetic energy drops can therefore is defined as:

$$S_c = v_e.\text{LAI} = q.v.\text{LAI} \tag{7.8}$$

The drop volume (v) is estimated using the Marshall-Palmer (1948) equation:

$$v = a.R^b \tag{7.9}$$

where parameters $a = 0.124$, $b = 0.63$, and

R -   Rainfall rate or intensity (mm.h^{-1}).

In order to operate the model for a particular vegetation type requires values for two vegetation specific parameters S_c^{max} and v_e^{max}. A functional relationship between S_c/S_c^{max} (equations 7.10a and 7.10b) and v is also required. Calder *et al.*, (1995) developed the following empirical exponential relationship from rainfall simulator experiments:

$$S_c/S_c^{max} = 1 \qquad\qquad \text{for } v < 0.065 \tag{7.10a}$$
$$S_c/S_c^{max} = 0.5 + 0.73.\exp(-5.5.v) \qquad \text{for } v > 0.065 \tag{7.10b}$$

Then, rearranging the Marshall-Palmer (1948) equation to determine R for $v < 0.065$ it can be established that $S_c/S_c^{max} = 1$ for $R < 0.36$ mm.h^{-1}. From field measurements of LAI and storage capacity for events with $R < 0.36$ mm.h^{-1}, the vegetation/species specific v_e^{max} can be calculated. By knowing the v from the Marshall-Palmer (1948) equation and S_c^{max}, the variable S_c can be calculated as the product of S_c/S_c^{max} and S_c^{max}.

The maximum elemental volume (v_e^{max}) does not change with the growth of the tree due to the linear relationship between S_c^{max} and LAI. The linear relationship between storage capacity and LAI for a given vegetation type of constant physiognomy and configuration has been corroborated by the results of Aston (1979), von-Hoyningen-Huene (1981), Pitman (1989), Liu, (1998) and van Dijk and Bruijnzeel (2001).

3.3   Climate database

In order to run the CABALA model and the "variable storage Gash" model, climatic data was required. Daily rainfall, maximum and minimum temperature, Penman-Monteith reference evaporation and radiation for the fifty year period from 1950-1999 (*cf*. Chapter 4) were obtained from the South African national quinary catchment database (Schulze *et al.*, 2009).

3.4   Scenario Modelling Process

The use of plausible scenarios to investigate the likely impact of climate change has many benefits. By changing a single variable or joint variables by small, but realistic increments from a baseline can:

- Gauge likely impacts,
- Determine thresholds of change,
- Determine where change is significant, and
- Determine which driver of climate change is more significant than others (i.e. temperature, rainfall or CO_2).

Nine plausible scenarios (excluding a baseline scenario) of possible climate change were selected. These scenarios (excluding those that include CO_2) are based on the scenarios used in previous studies in South Africa by Engelbrecht (2005) and Warburton and Schulze (2006). The abbreviations for each scenario that will be used on graphs and tables are shown in brackets. The scenarios used are as follows:

- Increase in CO_2 from 350ppm to 550ppm;   (CO_2)
- Increase in temperature by 1^oC and 2^oC;   (T+1; T+2)
- Increase in rainfall by 5% and 10%;   (R+5%; R+10%)
- Decrease in rainfall by 5% and 10%;   (R-5%; R-10%)
- Increase in temperature by 2^oC in combination with a 10% increase in rainfall and increase in CO_2 to 550ppm;   (T2+10%+CO_2)
- Increase in temperature by 2^oC in combination with a 10% decrease in rainfall and increase in CO_2 to 550ppm.   (T2-10%+CO_2)

The modelling process followed in this study is illustrated in Figure 7.3.

INPUT
- Species Parameters
- Climate Variables
- Site/soil parameters
- Regime

SCENARIOS
- Baseline - Current Rainfall, Temperature, Radiation & CO_2
- Scenario 1 - Increase CO_2 from 350ppm to 550ppm
- Scenario 2 and 3 - Increase temperture by 1°C and 2°C
- Scenario 4 and 5- Increase rainfall by 5% and 10%.
- Scenario 6 and 7 - Decrease rainfall by 5% and 10%.
- Scenario 8 - Increase temperature by 2°C, increase rainfall by 10%, and increase CO_2 to 550 ppm
- Scenario 9 - Increase temperature by 2°C, decrease rainfall by 10%, and increase CO_2 to 550 ppm

CABALA OUTPUT
- Leaf Area Index (LAI)
- Transpiration

VS GASH OUTPUT
- Canopy interception

Figure 7.3   Process flow diagram

3.5   Site selection

In order to assess the possible impact of climate change on South African commercial forest species, it was necessary to identify sites where both *Eucalyptus grandis* and *Pinus patula* would grow under all scenarios of climate change. To select the study sites, the Institute for Commercial Forestry Research (ICFR) Forest Productivity Toolbox (Kunz, 2004) was used to identify such areas shown by the 9x22 climate matrix in Figures 7.4 and 7.5. This was done by selecting all the quinary catchments that had a Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) that was in the optimum range for all scenarios for both *E. grandis* and *P. patula*. Once these areas were determined, the largest quinary catchment with good climate data in four different forestry areas were selected as shown in Figure 8.6. The selected catchments are B81B, H60B, K50A, and V11G. These catchments will be referred to according to the province in which they are located (i.e. B81B = Mpumalanga, H60B = Western Cape, K50A = Eastern Cape, V11G = KwaZulu-Natal) rather than their catchment number. It is important to note that the catchments selected are not necessarily representative of the whole province in which it is located, but are typical of forested catchments in that province.

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Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)								
	< 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21	> 21
< 700	Snow/Frost	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
700 - 725	Snow/Frost	Snow/Frost	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
725 - 750	Snow/Frost	Snow/Frost	Snow/Frost	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
750 - 775	Snow/Frost	Snow/Frost	Snow/Frost	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry
775 - 800	Snow/Frost	Snow/Frost	Snow/Frost	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry
800 - 825	Snow/Frost	Snow/Frost	Snow/Frost	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry
825 - 850	Snow/Frost	Snow/Frost	Snow/Frost	(Drought)	(Drought)	(Drought)	(Drought)	Too dry	Too dry
850 - 875	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	(Drought)	(Drought)	(Drought)	Disease	Too dry
875 - 900	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	(Drought)	(Drought)	Disease	Disease
900 - 925	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	(Drought)	Disease	Disease
925 - 950	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
950 - 975	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
975 - 1000	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1000 - 1025	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1025 - 1050	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1050 - 1075	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1075 - 1100	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1100 - 1125	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1125 - 1150	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1150 - 1175	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
1175 - 1200	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease
> 1200	Snow/Frost	Snow/Frost	Snow/Frost	Optimum	Optimum	Optimum	Optimum	Disease	Disease

Figure 7.4   Illustration of the 9x22 climate matrix for delineation of optimum/sub-optimum growth areas for *Eucalyptus grandis* (After: Kunz, 2004)

Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)								
	< 14	14 - 15	15 - 16	16 - 17	17 - 18	18 - 19	19 - 20	20 - 21	> 21
< 700	Snow	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
700 - 725	Snow	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
725 - 750	Snow	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry	Too dry
750 - 775	Snow	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry	Too dry
775 - 800	Snow	(Drought)	(Drought)	(Drought)	(Drought)	Too dry	Too dry	Too dry	Too dry
800 - 825	Snow	Optimum	(Drought)	(Drought)	(Drought)	Sub-optimum	Too dry	Too dry	Too dry
825 - 850	Snow	Optimum	Optimum	(Drought)	(Drought)	Sub-optimum	Disease	Too dry	Too dry
850 - 875	Snow	Optimum	Optimum	Optimum	(Drought)	Sub-optimum	Disease	Disease	Too dry
875 - 900	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
900 - 925	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
925 - 950	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
950 - 975	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
975 - 1000	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1000 - 1025	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1025 - 1050	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1050 - 1075	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1075 - 1100	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1100 - 1125	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1125 - 1150	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1150 - 1175	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
1175 - 1200	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease
> 1200	Snow	Optimum	Optimum	Optimum	Optimum	Sub-optimum	Disease	Disease	Disease

Figure 7.5   Illustration of the 9x22 climate matrix for delineation of optimum/sub-optimum growth areas for *Pinus patula* (After: Kunz, 2004)

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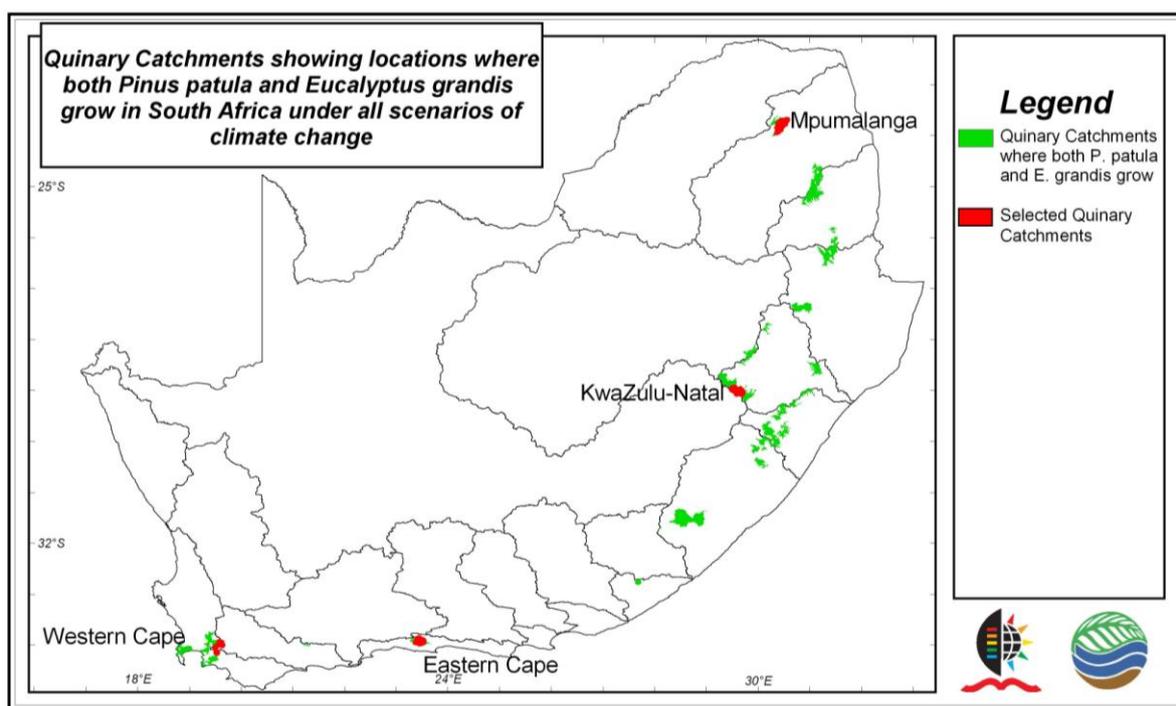
Figure 7.6   Map showing the location the study catchments and of the quinary catchments where both *P. patula* and *E. grandis* grow under all scenarios of climate change.

Table 7.2   Average historical rainfall and temperature for the selected catchments for the period 1950 - 1999.

Catchment	Mean annual precipitation (mm.year^{-1})	Average Maximum Temperature (^{o}C)	Average Minimum Temperature (^{o}C)
Mpumalanga	1110.6	25.1	14.3
Western Cape	1055.6	21.0	8.4
Eastern Cape	938.80	21.0	9.9
KwaZulu-Natal	1389.3	19.3	7.7

3.6   Baseline leaf area index data

Gush *et al*., (2001) extracted LAI values from Summerton (1995) for each of the three most common commercial forestry genera in South Africa, namely *Pinus*, *Eucalyptus* and *Acacia*. These values were assigned to each simulation site.

For each of the three commercial forestry genera, a representative age was assigned by Gush *et al*., (2001) based on analyses of the mean and median water use within a catchment with a normalised age distribution. The ages for each genus are as follows; 4 year old *Eucalyptus*, 7 year old *Pinus*, and 4

year old *Acacia mearnsii* (Gush *et al.*, 2001). This age and associated LAI is assumed to represent the median condition of all plantations in an area, is accepted in South African water resources planning and is thus considered an appropriate baseline for this study.

The LAI assigned to each genus for the four selected forestry areas based on the above mentioned ages are summarized in Table 7.3:

Table 7.3   Leaf area index (LAI) values for *Eucalyptus* and *Pinus* derived by Gush *et al*., (2001) for the four forestry zones in South Africa

Variable	LAI	
Zone / Genus	*Eucalyptus*	*Pinus*
Mpumalanga	3.5	3.5
KwaZulu-Natal	4.2	3.8
Eastern Cape	2.7	3.1
Zululand	4.4	3.8

3.7   Data analysis

The CABALA model (Battaglia *et al*., 2004) was used to simulate LAI and transpiration for *E. grandis* and *P. patula* for a baseline scenario (historical data from 1950 – 1999) and eight climate change scenarios at each of the study sites. An 8 year rotation was assumed for the *E. grandis* and a 15 year rotation for the *P. patula*. Therefore, using the baseline (historical) climate data from 1950-1999 (i.e. 50 years) 5 rotations were simulated for *E. grandis* and 3 rotations for *P. patula*. The daily simulated LAI and transpiration values were then accumulated (Schulze, 2010, pers. comm.) for the simulated period. The accumulated values for each scenario were then compared to the baseline simulation to determine the percentage change in LAI and transpiration for each of the selected catchments. The percentage change in LAI relative to the baseline simulation was then applied to the LAI values determined by Gush *et al*., (2001) to get a "new" *LA*I value (*cf*. Tables 7.8 and 7.9) for the 8 climate change scenarios. These "new" LAI values were then used as an input to model canopy interception under the above mentioned climate change scenarios using the variable storage Gash model.

4. RESULTS AND DISCUSSION

The results obtained from the simulations of LAI, transpiration and canopy interception for *E. grandis* and *P. patula* are presented in the subsequent section. The box and whisker plots presented in Figures 7.7 – 7.10 illustrate the maximum, minimum, 1st quartile (25th percentile), median (50th percentile) and 3rd quartile (75th percentile) of the simulated LAI and transpiration for all four selected catchments and 9 scenarios.

4.1 Leaf area index

The results of the simulated changes in LAI for *E. grandis* and *P. patula* are illustrated in the box and whisker plots shown in Figures 7.7 and 7.8. The percentage change for each study catchment is then summarised in Tables 7.4 and 7.5.
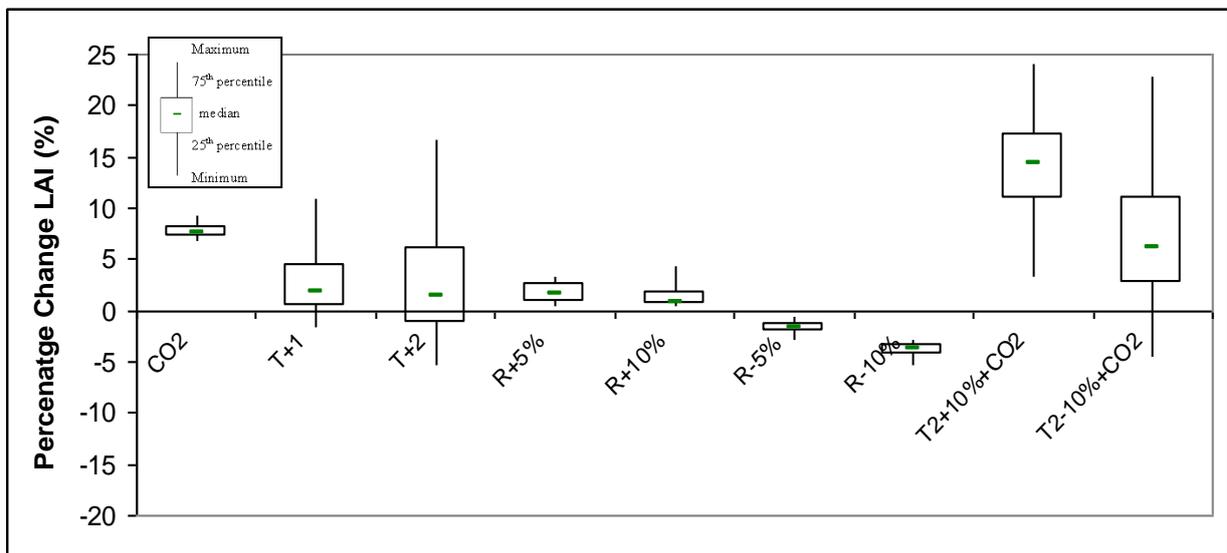
Figure 7.7   Box and whisker plot showing the simulated changes in LAI for *Eucalyptus grandis* for all sites for 9 plausible climate change scenarios.
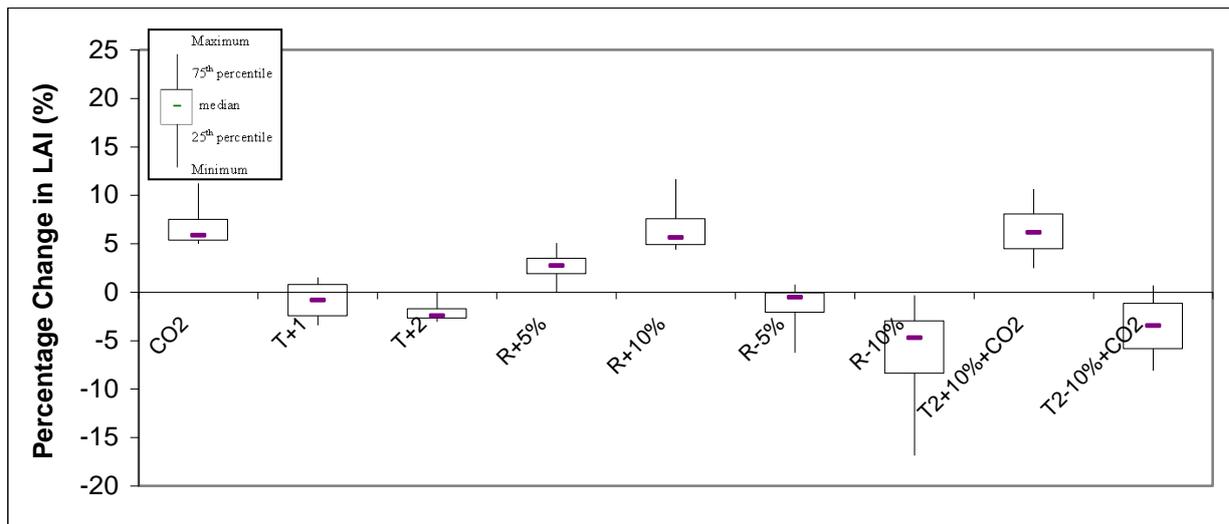
Figure 7.8   Box and whisker plot showing the simulated changes in LAI for *Pinus patula* for all sites for 9 plausible climate change scenarios**.**

Table 7.4   Percentage change in LAI for *E. grandis.*

E. grandis	CO_2	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Mpumalanga	9.19	-1.68	-5.36	3.15	0.39	-0.78	-3.52	3.14	-4.52
Western Cape	7.76	1.06	1.34	2.44	4.18	-2.97	-5.37	15.05	5.00
Eastern Cape	7.29	2.36	2.69	0.34	0.97	-1.71	-3.03	13.40	7.13
KwaZulu-Natal	6.75	10.81	16.51	0.85	0.69	-1.53	-3.98	23.96	22.64

Table 7.5   Percentage change in LAI for *P. patula.*

P. patula	CO_2	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Mpumalanga	5.43	-2.16	-2.61	-2.73	4.40	-0.35	-5.15	2.50	-0.38
Western Cape	6.29	1.49	2.45	2.97	6.21	-0.72	-5.60	7.20	0.65
Eastern Cape	11.20	-3.38	-3.03	5.04	10.61	-6.24	-16.82	11.63	-8.06
KwaZulu-Natal	5.02	0.54	-2.28	2.48	5.04	0.76	-3.83	5.79	-1.75

The change in LAI for *E. grandis* and *P. patula* presented in Figures 7.7 and 7.8 and Tables 7.4 and 7.5 show that for both species, there is an increase in LAI when there is just a change in CO_2. The scenario where only CO_2 is increased is similar to the results that would be obtained from FACE experiments, as FACE experiments *do not* consider changes in rainfall or temperature. There is an increase of between 6.75% and 9.19% for *E. grandis* and between 5.02% and 11.20% for *P. patula*. With an increase in temperature, the LAI for *E. grandis* generally increases, while there is a general decrease for *P. patula*. In KwaZulu-Natal where there is the lowest mean annual maximum temperature and the highest rainfall, there is a large increase in LAI of up to 16.51% because the trees are neither water nor temperature stressed. In Mpumalanga, which has the highest mean annual

maximum temperature, there is a decrease in LAI with increased temperature for both *E. grandis* and *P. patula*, as the trees become temperature stressed and decrease their LAI to try decrease the amount of transpiration. With an increase in rainfall, there is a general increase in LAI for both *E. grandis* and *P. patula*. The increase in LAI is greater for *P. patula* than *E. grandis* with an increase of as much as 10.51% in the Eastern Cape which is the catchment with the lowest mean annual rainfall. Both *E. grandis* and *P. patula* show a decrease in LAI with a decrease in rainfall. *P. patula* responds more to a reduction in rainfall than *E. grandis*, with a decrease in LAI of as much as 16.82% in the Eastern Cape, which has the lowest MAP. Conversely, *P. patula* in KwaZulu-Natal had the smallest decrease in LAI with a decrease in rainfall as the KwaZulu-Natal catchment has the highest MAP. For the scenario where the temperature is increased by 2°C, rainfall is increased by 10% and CO_2 is increased to 550 ppm, both *E. grandis* and *P. patula* increase LAI. The largest increase in LAI for *E. grandis* is 23.96% in the KwaZulu-Natal catchment, while the largest increase in LAI for *P. patula* is 11.63% in the Eastern Cape catchment. The smallest increase in LAI for both *E. grandis* and *P. patula* is in the Mpumalanga catchment. The scenario with an increase in temperature of 2°C, a decrease in rainfall by 10% and an increase in CO_2 to 550 ppm show that for *E. grandis* there will be an increase in LAI for all catchments other than in Mpumalanga. The largest increase in LAI is in KwaZulu-Natal, even with a decrease in rainfall. This is because the KwaZulu-Natal catchment has the highest MAP and lowest annual average maximum temperature and therefore is not water stressed with the reduction in rainfall and the increase temperature. Also, with the increased CO_2 concentration, the stomatal resistance is increased and the trees are more water efficient due to reduced transpiration. Unlike *E. grandis*, *P. patula* shows a general decrease in LAI with increased temperature, decreased rainfall and increased CO_2. *P. patula* is more susceptible to water and temperature stress than *E. grandis* even with the increase in CO_2.

4.2   Transpiration

The results of the simulated changes in transpiration for *E. grandis* and *P. patula* are illustrated in the box and whisker plots shown in Figures 7.9 and 7.10. The percentage change for each study catchment is then summarised in Tables 7.6 and 7.7.
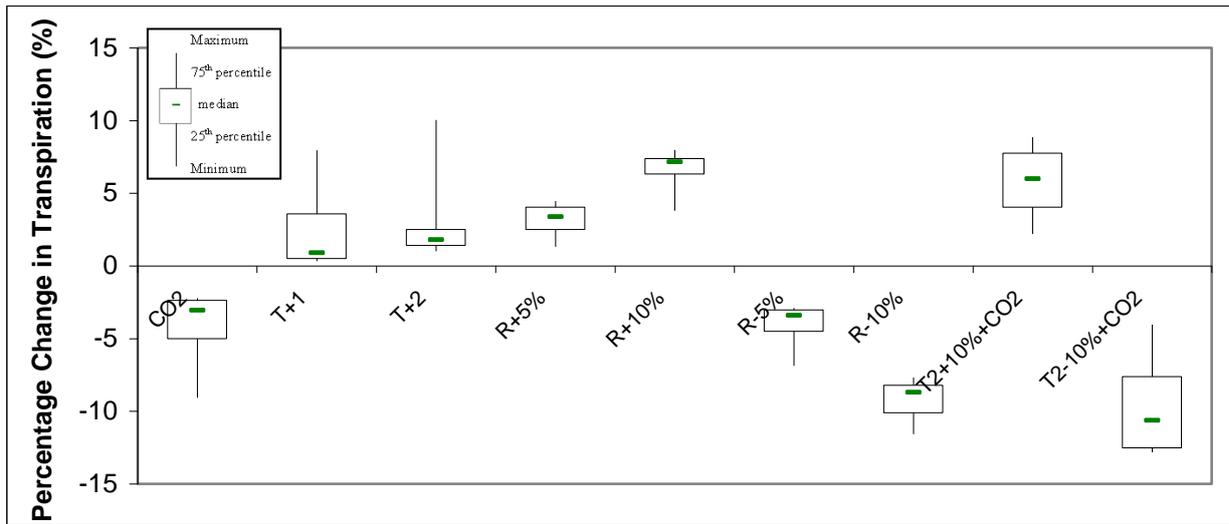
Figure 7.9   Box and whisker plot showing the simulated changes in accumulated transpiration for *Eucalyptus grandis* for all sites relative to a current day baseline.
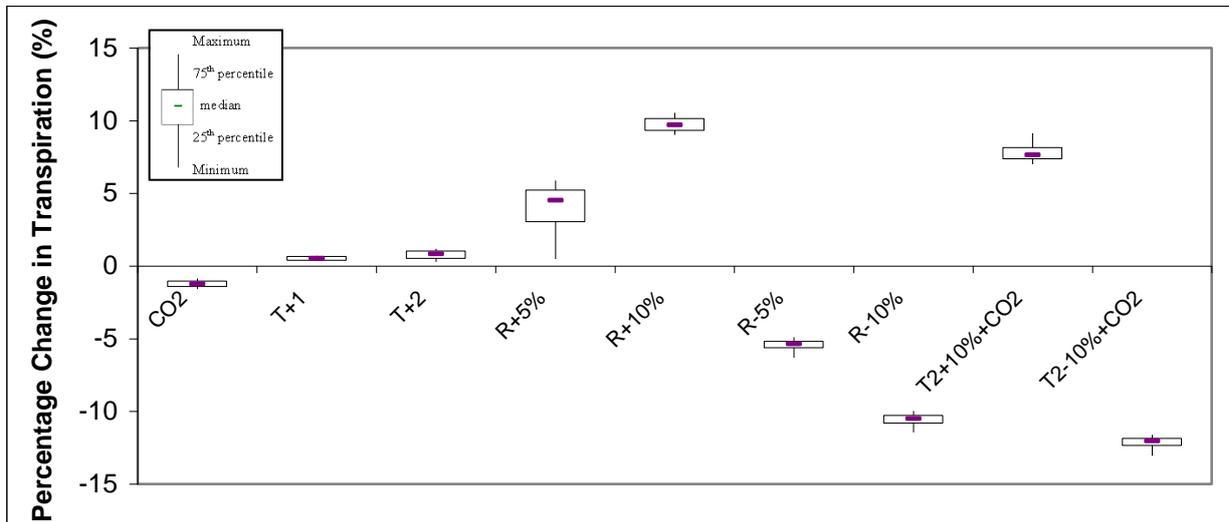
Figure 7.10   Box and whisker plot showing the simulated changes in accumulated transpiration for *Pinus patula* for all sites relative to a current day baseline.

Table 7.6   Percentage change in accumulated transpiration for *E. grandis*.

E. grandis	CO_2	$T+1^oC$	$T+2^oC$	R+5%	R+10%	R-5%	R-10%	$T+2^oC\_R+10\%\_CO_2$	$T+2^oC\_R-10\%\_CO_2$
Mpumalanga	-2.24	1.50	1.65	2.86	7.19	-2.93	-7.72	2.23	-12.45
Western Cape	-2.43	2.12	2.60	3.92	7.14	-3.74	-8.70	8.82	-8.80
Eastern Cape	-3.70	0.35	1.04	4.44	7.94	-6.86	-11.56	7.39	-12.81
KwaZulu-Natal	-9.05	7.93	10.01	1.34	3.82	-3.07	-7.91	4.60	-4.06

Table 7.7   Percentage change in accumulated transpiration for *P. patula*.

P. patula	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Mpumalanga	-1.10	0.65	1.17	4.04	9.41	-4.92	-9.99	7.03	-11.63
Western Cape	-0.87	0.37	0.02	5.00	10.02	-5.27	-10.62	7.83	-12.13
Eastern Cape	-1.38	0.38	0.98	5.87	10.53	-5.43	-10.38	9.12	-13.01
KwaZulu-Natal	-1.56	0.67	0.67	0.50	9.05	-6.28	-11.42	7.46	-11.94

The simulated results from the CABALA model of the change in transpiration are shown in Figures 7.9 and 7.10 and Tables 7.6 and 7.7. For the scenario with an increase in CO$_2$ from 350 ppm to 550 ppm there is a decrease in transpiration for both *E. grandis* and *P. patula*. However, the decrease in transpiration is small due to the "offset" of an increase in LAI. With just an increase in temperature there is once again not a large increase in transpiration for either *E. grandis* or *P. patula*. With an increase in rainfall both *E. grandis* and *P. patula* increase transpiration as both water availability and LAI increase. The largest increase in transpiration with increased rainfall for both *E. grandis* and *P. patula* is in the Eastern Cape catchment which has the lowest MAP. The smallest increases in transpiration with increased rainfall are in KwaZulu-Natal, which has the highest MAP and therefore the least water stressed catchment. A reduction in rainfall results in transpiration decreasing for both *E. grandis* and *P. patula* by as much as 11.56% for *E. grandis* and 11.42% for *P. patula*. The reduction in transpiration is as a result of a decrease in LAI and water availability. For the scenario with an increase in temperature, rainfall and CO$_2$, there is an increase in transpiration. Although, increased CO$_2$ suppresses transpiration, the combination of increased temperature, rainfall and LAI results in a net increase in transpiration. Results from the scenario with an increase in temperature and CO$_2$, but a reduction in rainfall show a decrease in transpiration of as much as 12.81% for *E. grandis* and 13.01% for *P. patula* in the Eastern Cape. This is due to the combined effect of increased stomatal resistance and a reduction in available water. Vegetation responses to climate change may allow for ecosystem water use to be resilient to stresses associated with increased temperatures, changes in CO$_2$ concentrations and changes in rainfall. Physiological adaptations (e.g. stomatal resistance) allow certain species to limit transpiration in response to changes in temperature, CO$_2$ and rainfall. Thus, ecosystems have multiple mechanisms to adjust to changes which may result in little to no detectable change in streamflow (Jones, 2011).

4.3   Canopy interception

In order to model canopy interception, the percentage change in LAI shown in Tables 7.4 and 7.5 were applied to the baseline LAI values derived by Gush *et al*., (2001). The new LAI values used to model canopy interception for each of the 9 climate change scenarios are shown in Tables 7.8 and 7.9.

Table 7.8   New LAI values for *E. grandis.*

E. grandis	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Mpumalanga	3.50	3.82	3.44	3.31	3.61	3.51	3.47	3.38	3.61	3.34
Western Cape	2.70	2.91	2.73	2.74	2.77	2.81	2.62	2.55	3.11	2.83
Eastern Cape	2.70	2.90	2.76	2.77	2.71	2.73	2.65	2.62	3.06	2.89
KwaZulu-Natal	4.20	4.48	4.65	4.89	4.24	4.23	4.14	4.03	5.21	5.15

Table 7.9   New LAI values for *P. patula.*

P. patula	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Mpumalanga	3.50	3.69	3.42	3.41	3.40	3.65	3.49	3.32	3.59	3.49
Western Cape	3.10	3.29	3.15	3.18	3.19	3.29	3.08	2.93	3.32	3.12
Eastern Cape	3.10	3.45	3.00	3.01	3.26	3.43	2.91	2.58	3.46	2.85
KwaZulu-Natal	3.80	3.99	3.82	3.71	3.89	3.99	3.83	3.65	4.02	3.73

For most scenarios there is not a large change in LAI for either *E. grandis* or *P. patula*. The largest increase in LAI is for *E. grandis* in the KwaZulu-Natal catchment for the scenario with increased temperature, rainfall and CO$_2$, where the LAI increased from 4.20 to 5.21. The changes in LAI for *P. patula* are generally smaller than for *E. grandis*. With the changes in LAI, there is a change in the storage capacity of the trees and therefore a change in the canopy interception. The results of the modelled canopy interception with the combined changes in LAI, rainfall and temperature are presented in Tables 7.10 and 7.11.

Table 7.10   Canopy interception results for *Eucalyptus grandis.*

E. grandis MP	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Rainfall (mm)	51183.60	51183.60	51183.60	51183.60	53742.78	56301.96	48624.42	46065.24	56301.96	46065.24
Interception (mm)	7559.18	7783.44	7517.00	7425.49	7897.52	8087.91	7277.06	6952.46	8158.34	6924.42
Interception (%)	14.77	15.21	14.69	14.51	14.70	14.37	14.97	15.09	14.49	15.03
Difference (%)		0.44	-0.08	-0.26	-0.07	-0.40	0.20	0.32	-0.28	0.26
Hist/scenario (%)		2.97	-0.56	-1.77	4.48	6.99	-3.73	-8.03	7.93	-8.40

E. grandis WC	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Rainfall (mm)	39428.30	39428.30	39428.30	39428.30	41400.72	43371.13	37456.89	35485.47	43371.30	35485.47
Interception (mm)	6032.20	6193.79	6055.46	6063.20	6295.20	6533.73	5761.67	5498.87	6765.49	5712.59
Interception (%)	15.30	15.71	15.36	15.38	15.21	15.06	15.38	15.50	15.60	16.10
Difference (%)		0.41	0.06	0.08	-0.09	-0.23	0.08	0.20	0.30	0.80
Hist/scenario (%)		2.68	0.39	0.51	4.36	8.31	-4.48	-8.84	12.16	-5.30

E. grandis EC	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Rainfall (mm)	53219.30	53219.30	53219.30	53219.30	55880.27	58541.23	50558.34	47897.37	58541.23	47897.37
Interception (mm)	8436.58	8669.98	8506.92	8518.59	8725.06	9024.13	8100.34	7787.37	9412.11	8099.00
Interception (%)	15.85	16.29	15.98	16.01	15.61	15.41	16.02	16.26	16.08	16.91
Difference (%)		0.44	0.13	0.15	-0.24	-0.44	0.17	0.41	0.23	1.06
Hist/scenario (%)		2.77	0.83	0.97	3.42	6.96	-3.99	-7.70	11.56	-4.00

E. grandis KZN	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_ R-10%_ CO$_2$
Rainfall (mm)	65506.20	65506.20	65506.20	65506.20	68781.51	72056.82	62230.89	58955.58	72056.82	58955.58
Interception (mm)	11408.07	11727.46	11920.77	12188.82	11793.77	12121.50	10999.17	10533.01	13237.82	11775.54
Interception (%)	17.42	17.90	18.20	18.61	17.15	16.82	17.67	17.87	18.37	19.97
Difference (%)		0.49	0.78	1.19	-0.27	-0.59	0.26	0.45	0.96	2.56
Hist/scenario (%)		2.80	4.49	6.84	3.38	6.25	-3.58	-7.67	16.04	3.22

Table 7.11   Canopy interception results for *Pinus patula.*

P. patula MP	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_R-10%_CO$_2$
Rainfall (mm)	51183.60	51183.60	51183.60	51183.60	53742.78	56301.96	48624.42	46065.24	56301.96	46065.24
Interception (mm)	9188.86	9405.15	9097.48	9086.05	9348.20	9907.19	8903.49	8629.03	9837.12	8435.86
Interception (%)	17.95	18.38	17.77	17.75	17.39	17.60	18.31	18.73	17.47	18.31
Difference (%)		0.42	-0.18	-0.20	-0.56	-0.36	0.36	0.78	-0.48	0.36
Hist/scenario (%)		2.35	-0.99	-1.12	1.73	7.82	-3.11	-6.09	7.05	-8.19

P. patula WC	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_R-10%_CO$_2$
Rainfall (mm)	39428.30	39428.30	39428.30	39428.30	41400.72	43371.13	37456.89	35485.47	43371.30	35485.47
Interception (mm)	7782.33	8005.32	7841.22	7876.48	8114.48	8458.62	7529.11	7123.16	8494.61	7345.29
Interception (%)	19.74	20.30	19.89	19.98	19.60	19.50	20.10	20.07	19.59	20.70
Difference (%)		0.57	0.15	0.24	-0.14	-0.24	0.36	0.34	-0.15	0.96
Hist/scenario (%)		2.87	0.76	1.21	4.27	8.69	-3.25	-8.47	9.15	-5.62

P. patula EC	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_R-10%_CO$_2$
Rainfall (mm)	53219.30	53219.30	53219.30	53219.30	55880.27	58541.23	50558.34	47897.37	58541.23	47897.37
Interception (mm)	11157.20	11787.58	10972.03	10990.57	11751.43	12364.06	10503.60	9592.42	12419.16	10087.08
Interception (%)	20.96	22.15	20.62	20.65	21.03	21.12	20.78	20.03	21.21	21.06
Difference (%)		1.18	-0.35	-0.31	0.07	0.16	-0.19	-0.94	0.25	0.10
Hist/scenario (%)		5.65	-1.66	-1.49	5.33	10.82	-5.86	-14.02	11.31	-9.59

P. patula KZN	Baseline	CO$_2$	T+1°C	T+2°C	R+5%	R+10%	R-5%	R-10%	T+2°C_R+10%_CO$_2$	T+2°C_R-10%_CO$_2$
Rainfall (mm)	65506.20	65506.20	65506.20	65506.20	68781.51	72056.82	62230.89	58955.58	72056.82	58955.58
Interception (mm)	13815.56	14165.66	13852.51	13649.08	14345.70	14894.44	13506.29	12810.08	14949.85	12957.24
Interception (%)	21.09	21.62	21.15	20.84	20.86	20.67	21.70	21.73	20.75	21.98
Difference (%)		0.53	0.06	-0.25	-0.23	-0.42	0.61	0.64	-0.34	0.89
Hist/scenario (%)		2.53	0.27	-1.21	3.84	7.81	-2.24	-7.28	8.21	-6.21

The results for the modelled canopy interception are shown in Tables 7.10 and 7.11 for *E. grandis* and *P. patula* respectively. Although there were changes in LAI and hence changes in canopy storage capacity, there is very little change in canopy interception (as a percentage of gross precipitation) for both *E. grandis* and *P. patula*. For the scenarios where there is an increase in temperature there is a small increase and decrease in LAI which result in very small changes in interception. For the scenarios where there is an increase in rainfall, there is also an increase in LAI and hence an increase in canopy storage capacity. Therefore, while the volume of water intercepted is greater than the baseline scenario, the interception as a percentage of gross precipitation is very small. This is because the increase in LAI offsets the increase in rainfall, resulting in a very small change in interception. Similarly with the scenarios where rainfall is decreased, there is a decrease in LAI, resulting in the reduced rainfall being offset by the smaller canopy storage capacity. The scenario with increased temperature, rainfall and CO$_2$ shows a similar result to the other scenarios, where the increase in LAI offsets the increase in rainfall resulting in a negligible change in interception. The greatest change in interception is for *E. grandis* in the Kwazulu-Natal catchment for the scenario where temperature and CO$_2$ are increased and rainfall is decreased. This is because there is an increase in LAI and therefore an increase in canopy storage capacity, but a reduction in rainfall. This results in more rainfall being intercepted, but there is less rainfall. Even so, there is only a 2.56% increase in interception as a percentage of gross rainfall.

5. CONCLUSION

This study highlights the complex interactions and feedbacks between climatic, physiological and hydrological responses within the forest ecosystem under scenarios of climate change. The response of both *E. grandis* and *P. patula* to changes in temperature, rainfall and CO_2 vary between the study catchments highlighting the spatial variability of the physiological and hydrological responses to any future changes in climate. Leaf area index is a critical model variable to describe forest characteristics and their potential episodic or long-term physiological and hydrological changes under climate change. The response of transpiration to the climate change scenarios highlights the interactions and feedbacks between climatic/atmospheric and physiological changes. For example, with increased CO_2, the increase in LAI is compensated for by reductions in stomatal conductance, leading to slightly lower transpiration rates. With changes in LAI under scenarios of climate change, canopy interception does not change greatly as it is largely offset by the altered rainfall regime. This is best illustrated by considering the scenarios of increased rainfall. With an increase in rainfall, there is an increase in LAI and hence a higher canopy storage capacity. However, the increase in rainfall offsets the increase in interception, resulting in canopy interception remaining a more or less constant fraction in the forest water balance when expressed as a percentage of gross precipitation. The only scenario where there is likely to be a large increase in canopy interception is when there is only an increase in CO_2, and the rainfall and temperature remain unchanged. This is however, the least likely scenario as there is already evidence of an increase in temperature. One of the problems with the scenarios is that they do not tell us much about how the climatic variables affecting interception will change e.g. number of raindays and rainfall intensity. Effectively, results show that natural climate variability is more important than climate change in influencing canopy interception in South Africa. Therefore, under future climates it can be concluded that there will only be a small change in canopy interception, but ranging from 15-22% of annual precipitation it remains an important consideration in water resources planning under any scenario.

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CHAPTER 8

How do hydrological process studies improve our science: lessons from interception studies

How do hydrological process studies improve our science: lessons from interception studies

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ABSTRACT

Understanding of the hydrological cycle and processes such as interception span as far back as the times of the Renaissance, when Leonardo da Vinci (1452-1519) first described it. da Vinci's shift from a religion centred paradigm to a science centred paradigm of empiricism and deduction changed the way we do science and highlighted the need for observations and data collection. Science is founded on observations and the development of hydrological science relies greatly on the continued measurement of natural processes. The difficulty of making hydrological measurement lies in the great spatial and temporal variability of processes. The hydrological cycle involves many interconnected processes, separation points, feedback loops, and stocks. One such process (which is also a separation point, feedback, and stock) that is often ignored or considered insignificant is interception. Interception studies are a good illustration of how trhe science of hydrology has and will continue to evolve. Hydrology should be considered an interdisciplinary science that encapsulates many different Earth sciences, as well as social sciences. Hydrological modelling plays an important part in modern hydrology, for data processing and analysis, exploring scenarios, developing hypothesis and parameter sensitivity, to mention but a few. However, models need to be structured and used correctly and rely on good input data. Therefore, modelling should be used to synthesise observations, but can never replace them.

1. INTRODUCTION

Studies to improve our understanding of the hydrological cycle and processes such as interception are not new. Leonardo da Vinci (1452-1519) may be recognised as one of the greatest minds of our time, but few people know that his achievements span wider than just painting, anatomical descriptions of the human body, or the development of new weapons and innovative concepts of warfare. Leonardo da Vinci's legacy contains a large number of writings that document his efforts to describe and

understand the water cycle, the basis of hydrology. da Vinci may therefore be considered one of the founding fathers of hydrology. He was also an advocate of the Renaissance period; where there was a clear paradigm shift from the dominant religion-centred paradigm of the Middle Ages to a more "science centred" paradigm, based on empiricism and deduction (Pfister and Savenije, 2006). But has anything really changed? We still base most of our research on empiricism and deduction. And perhaps it's only our tools that have changed.

Leonardo da Vinci dedicated much of his time to understanding the movement, circulation and physical characteristics of water in its different forms. da Vinci's approach was simple and clear, as he stated that "whenever speaking about water, you have to keep in mind that you first have to invoke experience, before reasoning"(McCurdy, 1942 in Pfister and Savenije, 2006). If one disaggregates this statement, then; the experience can only be gained through the identification of relevant questions such as 'why water is moving and why the movement stops; why it is slowing down or accelerating, and…how it moves upward in the air, under the effect of solar heat and then fall as rain' (McCurdy, 1942 in Pfister and Savenije, 2006). The 'experience' referred to by da Vinci may be considered as a form of empiricism and so provides the first example of the need and use for hydrological observations. In the time since da Vinci, and in parallel with the emergence of the observation based scientific method, many hydrologists have recognised the need for observations of phenomenon over time and space. Hence, networks of stations with hydrological records that are both reliable and of sufficiently long duration are considered a prerequisite for water resources management and planning. Therefore today, the challenge lies in bridging the gap between field observations, the understanding of relevant hydrological processes such as interception and their spatial variability in space and time, the elaboration of concepts, the application of models and eventually their transposition to ungauged basins, together with an ongoing recognition of the limitations of these.

In this paper, we use "interception", the evaporation of water trapped by land cover during and directly after rainfall, as a means to explore the evolution of hydrological science.

2.   THE IMPORTANCE OF HYDROLOGICAL MEASUREMENTS

Arguably, it is "science" that has seen humanity gain dominion over all other living organisms occupying Earth. The role of science is ultimately to understand the world in which we live and through this understanding make Earth a better place to live on. Generally, "science" can be considered the process of acquiring data about a physical entity, using general laws or experimentation, and the processing of that data to yield information and applying that information as knowledge to solve specific problems and allow prediction. Science is founded on observations and

the development of hydrological science relies greatly on the continued measurement of natural processes (Zepp, 1994; Silberstein, 2006). To illustrate this point, consider a hypothetical laboratory experiment as depicted in Figure 8.1, relating two quantities x and y. If focussing in on Window A, it may be concluded that the quantity y is not related to x and that it may have a constant a plus/minus an error term. If the experiment is carried out for a longer period (Window B), a more clear relationship emerges, which may be modelled as a parabolic function. If one continues even further (Window C), then the parabolic function may be disregarded in favour of a cosine function (Koutsoyiannis, 2006). If this experiment is continued even further, the cosine function may even prove inadequate and a more complex function may have to be fitted. Similar patterns are observed in natural hydrological processes, such as rainfall and streamflow records.
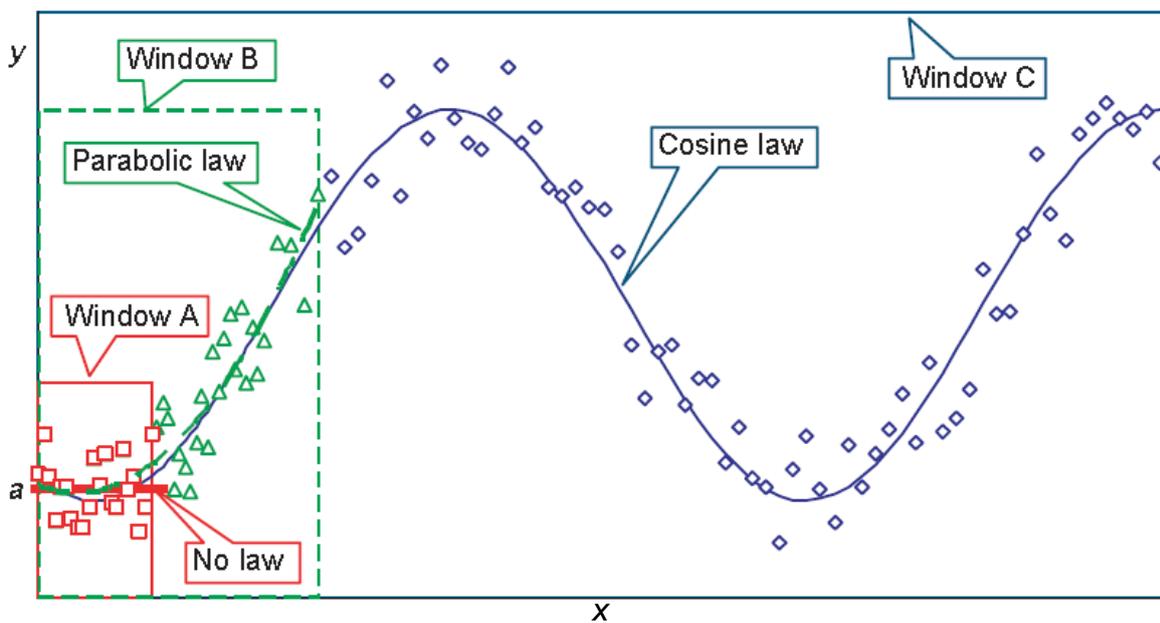
Figure 8.1   Depiction of a hypothetical example of successive experimental attempts to discover a law relating quantities x and y (After: Koutsoyiannis, 2006).

Therefore, to understand processes such as interception better, we need an adequate time series of data to account for inter and intra-seasonal and inter-annual variability of climatic and vegetation factors. If the data length is not long enough, rainfall variability between seasons or between a "wet" and "dry" year will not be accounted for. As shown in Chapter 2, there may be large differences in the rainfall characteristics from year to year, in terms of depth, duration, frequency and intensity. The result of this variability in rainfall characteristics is a marked difference in interception and storage capacity (*cf.* Chapter 2). Therefore, if field measurements are not taken for a sufficiently long time, these differences may not be exposed, and a misleading result presented. Similarly, vegetation changes seasonally, particularly deciduous vegetation, and over a period of a year the trees may have grown sufficiently to have a marked change in the storage capacity of the canopy. The task of measuring hydrological processes is, however, much more difficult than a laboratory experiment. The hydrologist

cannot repeat or accelerate the rate of field experiment measurements to quickly investigate a wider range of variations. Instead, the hydrologist has to keep observing until nature produces a wider range of phenomena, and the evolution of a hydrological process is unique (Koutsoyiannis, 2006). Three of the greatest problems for the hydrologist are to (1) quantify the amount of water in the different phases of the hydrological cycle, and (2) evaluate the rate of transfer of water from one phase to the other. The third challenge facing hydrologists is that in the past, historical data could be used to calibrate hydrological models or from which we could extrapolate in time. This approach remains valid so long as system changes are not too severe and that the assumption of stationarity can be justified. Stationarity is the idea that natural systems fluctuate within an unchanging envelope of variability. However, to make predictions in a changing environment where the system structure may not be invariant or in which the system might exhibit previously unobserved behaviour due to new thresholds being exceeded. In such cases, past observations may not be sufficient to serve as a guide to the future (Wagener *et al.*, 2010). Therefore, we need to continue to measure hydrological processes so that our understanding of the changes in thresholds and processes can be improved under a changing environment.

The main challenge in catchment hydrology is to advance our understanding of how catchments work, the variability, and the heterogeneity that dominate the catchments response (Uhlenbrook, 2006). This includes all processes, no matter how small or "insignificant" they may seem, and all of which requiring extensive fieldwork at different spatial scales. Spatial scales vary from small headwaters to large catchments. Temporal scales vary from short events (seconds, minutes, hours) to medium-term processes (days, months), long-term processes (years) and trends (decades, centuries). The speciality and difficulty of catchment hydrology is that it focuses on the whole catchment, wherein all hydrological storages and fluxes interact in complex non-linear ways (Uhlenbrook, 2006) and that changing perspective, viewpoint, and/or observation scale often reveals surprising or unexpected results.

The hydrological cycle involves many interconnected processes, separation points, feedback loops, and stocks (Savenije, 2005). One such process (which is also a separation point, feedback, and stock), but which is often ignored or considered insignificant, is interception. Often, if it is included in hydrological or water resources studies, it is considered to be a constant. While this is better than ignoring it completely, interception is definitely not a constant in the hydrological cycle and varies over space and time. In hydrological analysis, ignoring interception is a fundamental error, as several studies show that it certainly is not an insignificant hydrological process. Beven (2001) states that evaporation from intercepted water on leaf surfaces in rough canopies can be very efficient and a significant portion of the water balance. Calder (1990) shows that in upland forest catchments in Britain, interception may amount to 35% in areas with rainfall of 1000 mm.year^{-1}. It can be higher in

areas with lower rainfall, amounting to 40-50% in areas with rainfall of between 500-600 mm.year^{-1}. If one considers the starting point of the hydrological cycle as precipitation, then the first process is interception. Water is retained before it can continue on its path in the hydrological cycle and allows for a direct feedback to the atmosphere. However, depending on the definition of interception, it may be considerably larger. In Calder's (1990) study, his narrow definition of interception is the difference between gross precipitation and throughfall. This is however not a very useful definition of interception when considering the full hydrological cycle, as it does not cater for evaporation from the land surface. Therefore, it is important to define exactly what is being referred to as interception when composing a research question and designing an experiment.

Firstly, one needs to decide whether interception is a stock or a flux or a combination of both. If interception is referred to as a stock, then it is the amount of precipitation that is temporarily stored on a surface (man-made or natural) to be evaporated shortly after or during the event. This is actually the interception storage capacity. If interception is considered a flux, then it is the evaporation of precipitation expressed in mm per unit time. Thus, it can be argued that a better way of considering interception is as both a stock and a flux. Interception is then the sum of the rate of change of intercepted precipitation and its evaporation (Savenije, 2005). Mathematically this is expressed as Equation 8.1:

$$I = \frac{dS_c}{dt} + E \qquad\qquad (8.1)$$

Where:

I - interception loss (mm.day^{-1}),

S_c - interception storage capacity (mm.day^{-1}), and

E - evaporation from interception (mm.day^{-1}).

Secondly, it is important to specify the location of the interception process in the hydrological cycle. The most obvious place to do so is at the partitioning point between the atmosphere and where rainfall is separated into interception, surface runoff and infiltration. Therefore the interception storage or stock (S_c) is located at the first partitioning point. Following this definition, the interception process includes evaporation from wet leaves, wet land cover (including man-made structures), wet mulch and forest floor litter and even the first few millimetres of wet soil. According to Savenije (2005), the wet soil surface should not be included as part of soil moisture that feeds the transpiration process. The wet soil surface feeds back the intercepted water to the atmosphere through direct evaporation and not via the delayed process of transpiration. This wet "crust" of soil which dries out within a day of the rainfall event may intercept several millimetres of rainfall. Simply put, interception is the fast evaporation mechanism that dries moist land cover during and directly after the rainfall event, having an average residence time in the order of a day. To measure and fully understand all the processes in

the hydrological cycle, requires knowledge drawn from plant physiologists, meteorologists, soil scientists as well as hydrologists, so an interdisciplinary approach that makes use of detailed knowledge, data, tools and two-way interactions between neighbouring disciplines will benefit interception studies.

3.   HYDROLOGY AS AN INTERDISCIPLINARY SCIENCE

Although hydrology has become considered as a distinct geoscience in its own right, it is implicitly an interdisciplinary science. According to Shamsi (2007), hydrology may be defined as "the science that encompasses the occurrence, distribution, movement and properties of the waters of the Earth and their relationship with the environment within each phase of the hydrological cycle." It is due to waters relationship with almost every environmental process, whether physical or biological, that ultimately makes it an interdisciplinary science. However, as much as hydrology may be considered an interdisciplinary science, there are strong arguments for what hydrology should not be viewed as. Hydrology is not merely a collection of methods or techniques that can be used to predict the future behaviour of water resources; nor is it an "assumption" science in which unexplained phenomena within the hydrological cycle are patched using previous experience to give reasonable or acceptable results (Klemes, 1986). Although hydrology is a science that is based on components derived from other fundamental and applied sciences, it goes beyond just being a problem solving approach which relies solely on observations made by other disciplines, but actually has great capacity of ingenuity based on its sound scientific basis (Schulze, 1993).

Hydrology is complex when considering just the physical environment as depicted in Figure 8.2, but the importance and attraction of studying catchment hydrology in a holistic manner lies in the fact that pure scientific interests (e.g. runoff generation, residences times of water in different systems, water quality, spatio-temporal patterns of water availability to plants etc.) overlap with practical water management and engineering, and societal concerns (Uhlenbrook, 2006). Although hydrology has made large strides in understanding the behaviour of small, relatively homogenous systems over relatively short time scales, more research is needed to understand the hydrological systems complexity at larger scales (typically catchment scale and larger), and over longer time scales (decadal to century scale). System complexity under these circumstances arises from non-linear, heterogeneous, and highly dynamic processes involving hydrological, biogeochemical, ecological, and human (societal) systems, with strong interactions and feedbacks, sometimes producing unexpected behaviour at larger scales, that would otherwise not be easily derived from understanding the components of the system in isolation and in a non-interdisciplinary manner (Wagener *et al*., 2010).
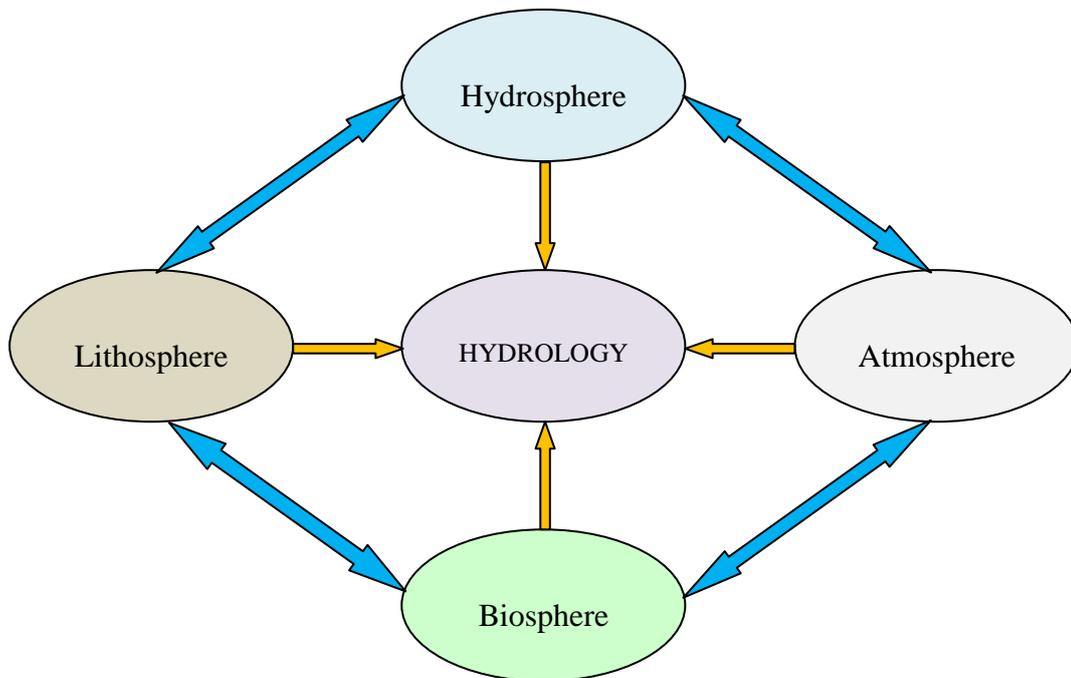
Figure 8.2   A schematic of the interconnected physical spheres that form the foundation of hydrology.

As society is faced with global change adaptation and planning, water managers are turning to science for answers due to concerns about water resource availability and quality. Society still needs information on hydrological processes at the catchment scale and smaller because, Wilson *et al*., (2010) suggest that although the hydrology community has significantly improved its understanding of such processes, there is a need for a new and integrative foundation of knowledge. Hydrology must not only reach beyond disciplinary boundaries but also forge broad connections with natural and social sciences to make water cycle predictions at regional and global scales. Climate change is one such global issue and is likely to have an impact on processes such as interception. If one is to accept the hypothesis that under climate change conditions, with increased atmospheric CO_2, temperatures, and in some areas an increase in precipitation, the canopies will become denser, thereby facilitating a greater canopy storage capacity. If this hypothesis is true, then under climate change, interception may in fact become a larger component of the forest hydrological cycle than transpiration. In order to test this hypothesis, a plant physiological model output is required as an input into a hydrological model, highlighting the importance of interdisciplinary science within hydrology, as well as the usefulness of models, which will be discussed in the subsequent section. Ultimately, these dynamics and feedbacks under climate change will have an impact on the amount of runoff reaching rivers and therefore the amount of water available for human consumption, industrial use, agriculture, environmental flows etc, but by how much is still uncertain. Therefore, within the study of hydrology and in hydrological modelling, there is an even greater need for the integration of other disciplines such as climatology, meteorology, plant physiology, ecology, as well as the social sciences in the future for water resources management and planning, as well as a recognition of the complexity of these interactions.

4.   THE IMPORTANCE AND IMPERFECTIONS OF MODELS

Hydrological models will continue to be an important tool for water resources management and planning now and in the future. While models of the water cycle have been in existence since at least the ancient Greeks, mathematical hydrological modelling probably only began in 1856 when Darcy published his analysis that water flows down a pressure gradient at a rate dependant on the properties of the medium (Silberstein, 2006). In more recent times, the biggest advance for modelling the "reverse flux" (i.e. evaporation) came in 1948 when Penman modelled evaporation based on data collected during World War II. This was elegantly added to by Monteith (1965). Since then, vegetation-water interactions have been added. Although, Horton (1919) first described interception loss by an equation with respect to evaporation rate during a rainfall event and canopy storage capacity, many researchers have improved upon his work to develop canopy interception models (Merriam, 1960; Gash, 1979; Massman, 1983; Calder, 1986; Whitehead and Kelliher, 1991; Gash *et al.*, 1995, van Dijk and Bruijnzeel, 2001; Robin, 2003). But, models are simply a perception of how a system/process works. "It is a hypothesis of the real world's functioning, codified in quantitative terms: a model of thought reflecting our theory (Savenije, 2009)." These hypotheses need to be tested against empirical evidence, once again highlighting the need for continual field measurements. When developing and testing hypotheses in hydrology there is a need for intuition, skill, imagination and creativity which are qualities that could as easily be attributed to art as to the science of hydrology (Savenije, 2009) and was intimated by da Vinci when he stated that "whenever speaking about water, you have to keep in mind that you first have to invoke experience, before reasoning"(McCurdy, 1942 in Pfister and Savenije, 2006). Koutsoyiannis (2010) identified six difficulties of modelling hydrological processes (or any other natural process). In comparison with a model, a natural system is;

1. far more complex,
2. has time-varying inputs and outputs,
3. has spatial and temporal extent, variability, and dependence,
4. has greater dimensionality (almost infinite),
5. has dynamics that to a large extent are unknown and difficult or near impossible to express deterministically, and
6. has parameters that are unknown.

Hydrologists need to understand that all models are (to a greater or lesser extent) wrong, almost by definition, and that our objective is to advance our understanding, not to find a good model (Beven, 2008, Savenije, 2009). "In fact, there is no such thing as a good model. As hydrologists we realise that a good model is characterised by an 'appropriate' model structure, 'good' model performance, and 'small' parameter and predictive uncertainty" (Savenije, 2009). Therefore, some suggest that the purpose of our research should be to develop a 'better' model that out-performs the current state-of-

the-art, and that is characterised by a 'more appropriate' structure, and a 'better' overall performance (Savenije, 2009) by accounting for all hydrological processes. The problem is that, the incorporation of more physical processes in a model leads to more parameters. The value of these parameters is normally poorly known resulting in the need for the model to be calibrated for each setting. However, limited calibration sets allow for a wide range of combinations of parameters that give the same result, known in hydrology as equifinality. Furthermore, insensitive parameters are poorly constrained, which is known as the problem of parameter identification (Kleinhans *et al*., 2009). The phenomenon of equifinality is even evident when modelling a single process such as canopy interception. If one considers the Gash interception model, then different combinations of gross precipitation (P_g), rainfall rate/intensity (R), evaporation (E), storage capacity (S_c) and canopy cover (c) can result in the same interception value.

Although adding more physical processes increases the number of parameters, interception cannot be disregarded or underestimated as this will lead to serious modelling errors, particularly when automated calibration techniques are used. If interception is modelled poorly or disregarded, then the error will be compensated for by other parameters to satisfy the goodness-of-fit criteria. This will jeopardize the physical representation of the hydrological model with all its possible related errors. A common mistake is to lump interception with transpiration which leads to an "over-dimensioning" of the soil moisture stock. If the interception process is forced through the transpiration process, the model can only represent the total flux and the time scale if the soil moisture stock is over-dimensioned. Therefore, if interception and transpiration are of roughly the same order of magnitude, then the modelled soil moisture would be approximately double what it should be (Savenije, 2005).

A further problem that hydrologists are continually faced with when modelling is non-stationarity. Currently, in most models stationarity is assumed, giving effect to the assumption that natural systems fluctuate within an unchanging envelope of variability (Milly *et al*., 2008). However, the assumption of stationarity has long been compromised by human disturbances in catchments. Furthermore, anthropogenic changes of the Earth's climate are altering the means and extremes of precipitation, evaporation, interception, transpiration and the rates of discharge in rivers. Non-stationarity of the climate results in non-stationarity in the vegetation and all their respective feedbacks. Therefore, in a non-stationary world, continuity of observations is critical. Some suggest that stationarity cannot be revived. Even with aggressive mitigation, continued warming is likely, given the residence time of atmospheric CO_2 and the thermal inertia of the Earths system (Milly *et al*., 2008). With such changes, there is going to be a need for a paradigm shift in hydrological science, including its approach to modelling and education from the "current" practice to a more holistic "future" practice as shown in Table 8.1.

Table 8.1   Key elements of the needed paradigm shift in hydrologic science (adapted from Wagener *et al.*, 2010)

Current	Future
Humans are external to the hydrological system	Humans are intrinsic to the hydrological system, both as agents of change and as beneficiaries of ecosystem services
Assumption of stationarity: past is a guide to the future	Nonstationary world: past is no longer a sufficient guide to the future, expected variability could be outside the range of observed variability
Transpiration is the dominant forest hydrological process	Under climate change conditions, physiological processes will change
Predicting response, assuming fixed system characteristics: boundary value problem with prescribed fixed topography, soils, vegetation, climate	Both system and response evolve: no longer a boundary value problem, boundary conditions and interfaces themselves evolve and are coupled. Becomes a complex adaptive system
Learning from studying individual places (often pristine experimental catchments) to extrapolate or upscale to other places	Comparative hydrology: learning from individual places embedded along gradients (e.g. changing climate, human imprint) and across spatial scales
Hydrologists as analysts of individual processes or features at small scales (akin to a microscope) or as synthesists of whole system behavior at large scales (akin to a telescope)	Hydrologists as both analysts and synthesists (akin to the macroscope) studying the coupled system across a range of time and space scales
Observations to characterize input-output behavior in individual (mostly) pristine places	Observations to track the evolution of both structure and response in coupled systems and subsystems
Observe and analyse pristine places and extrapolate to make predictions of human impacts	Observe and analyse real places where humans live and interact with the hydrological system at a range of scales
Model predictions derive credibility by reproducing historical observations	Model predictions derive credibility via a more in-depth diagnostic evaluation of model consistency with underlying system and testing behavior outside of observed range
Observation, prediction (modelling) and management are separate exercises (without feedbacks	Real-time learning: observations (sensing, including participatory human sensing), modelling and management are interactive exercises with feedbacks and updating
Strong separation between engineering and science approaches to hydrology education	Integration of qualitative and quantitative aspects in a holistic teaching of hydrology
Focus on teaching established solutions to current problems	Focus on teaching of evolving skill sets with a strong scientific basis that can be adapted to solving new problems and to understand new phenomena

5.   MODEL UNCERTAINTY, VERIFICATION AND VALIDATION

It is well known that there is great uncertainty in models. There are two main reasons for model uncertainty. Firstly, incorrect model structure and conceptulisation, and secondly, errors in parameter estimation (Silberstein, 2006). Considering Figure 8.3a, if the model is assumed to have the correct structure, models may be improved by adding more processes and hence complexity, which requires more parameters. Thus the structural uncertainty may decrease, but the parameter uncertainty increases. Figure 8.3a illustrates a well structured model that fits reality, with cumulative errors growing as the number of parameters increase, but the structural errors diminish with extra complexity. Conversely, if one considers Figure 8.3b, which illustrates a flawed model structure, no

amount of parameters can reduce the error, and the model can only reach its structural accuracy and not its parametric accuracy. In this case, there is an opportunity for scientific progress because the only way to reduce the errors is by improving the model structure. Thus, we may learn when models fail to reproduce reality, but this is only possible if we have real data with which to compare our models (Silberstein, 2006). Stirzaker *et al*., (2010) suggest maintaining a requisite simplicity when modelling complex systems. Requisite simplicity attempts to discard some detail, while retaining conceptual clarity and scientific rigour.
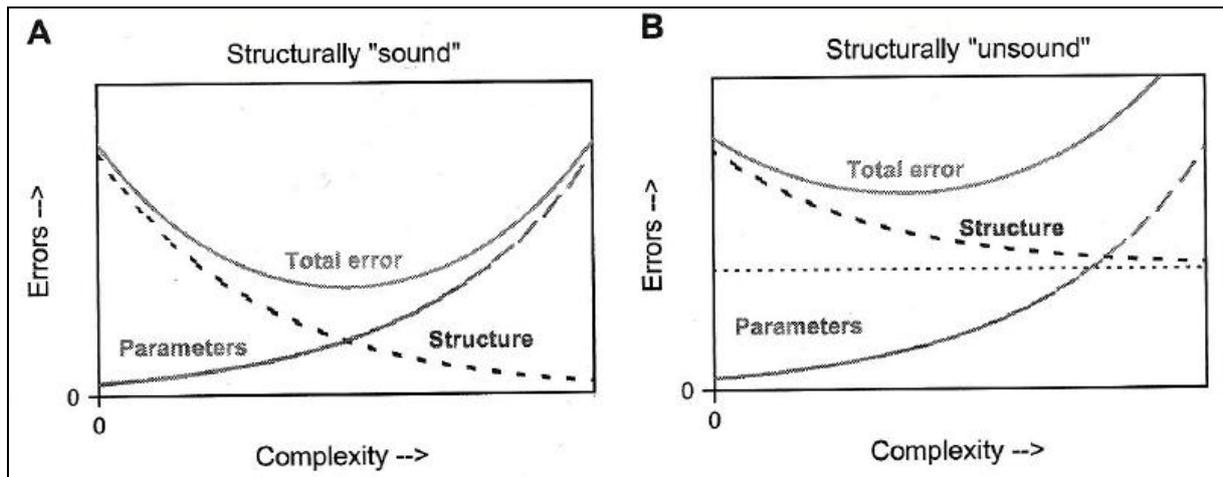
Figure 8.3   Notional components of model prediction error. (a) structurally sound model, (b) structurally unsound model (After: Silberstein, 2006)

The traditional scientific method is to propose a hypothesis and then set out to test whether it is untrue. However, this approach seems to have been lost in many modelling studies. Typically, a scientist takes a model, or develops one, and sets out systematically to *invalidate* it. However, papers are usually written from the viewpoint of verification or validation, when in fact this can never happen (Silberstein, 2006). While most modellers are concerned about validating their models there is a philosophical question of whether they can be validated or rather verified? According to Oreskes *et al*., (1994) the word "verify", derived from the Latin word *verus*, meaning true, implies an assertion or establishment of truth. Models can only be verified or validated in a mathematical or engineering sense in a closed system, where within acceptable limits they can be demonstrated to reproduce observations. Numerical models may contain closed mathematical components that are verifiable, such as an algorithm within a computer program may be verifiable. The reason that mathematical components are subject to verification is because they are part of a closed system that includes claims that are always true as a function of the meanings assigned to the specific symbols used to express them. However, hydrological models or even models representing a single process such as interception, that use these components are never closed systems. Oreskes *et al*., (1994) suggests that the reason that they are not closed systems and therefore cannot be verified is that there are inherently too many unknowable parameters and processes. They also argue that a model may be valid in the

sense that legal arguments are valid, in containing no logical or demonstrable flaws, and in the same sense legal arguments are valid until proven otherwise.

In a complex adaptive system such as the hydrological cycle, there are usually a large number of non-linear relationships. These relationships are multiple where any component may link to many others and there are always feedbacks (Cilliers, 2005). In a changing non-linear environment, there may be something that appears to be unimportant now, but may prove to be vitally important in the future. Therefore, dealing with complex systems demands a degree of humility from hydrologists because our knowledge is limited and there will be surprises (Stirzaker *et al*., 2010). Therefore, there needs to be a willingness to reject a model or hypothesis that may not perform well currently or in the future, as it was developed under a historical environment (i.e. a model or hypothesis that is currently valid, may not be valid in the future). For example, in terms of canopy interception, the hypothesis that under a changing climate, with a change in temperature, rainfall and CO_2, canopy interception will become a more dominant process may have to be rejected. This may be due to factors that have not been considered when modelling the physiological and hydrological responses to these changes, or, there may be a flaw in the model(s) structure.

Models are however extremely useful and serve many purposes. They provide a framework to assemble our process understanding and to explore implicit behaviour that results from that understanding. Models are also a useful tool for testing data, to check for inconsistencies and errors, and to fill in missing information. This is particularly useful when considering the inherent difficulty in hydrological measurements, which are susceptible to systematic errors. Modelling therefore also gives us a method to explore the implications of our measurements, and to not always take them at "face value". In fact, this may be the most useful application of models, because they help structure scientific enquiry that can expose further details behind observations (Silberstein, 2006; Milly *et al*., 2008). Models may be used because they are much cheaper and faster than doing real experiments. Consequently, the most widely publicised and commercial use of models is probably for scenario exploration as well as the assessment of existing conditions, such as water resources modelling. These may be options for system management or exploring possible outcomes under a range of different input conditions, perhaps depending on future climate, political or economic scenarios. They may also be used to make forecasts with specific timeframes in order for decision makers to react correctly and in time (Schulze, 2007). Similarly, models can be used to demonstrate the effect of actions or non-actions to stakeholders.

6.   CONCLUSION

All processes which affect the movement of water are important and a hydrologist should consider the hydrological system in its entirety. Even those processes that are often deemed to be "insignificant" such as interception can be critical in making accurate decisions although interception is definitely not an insignificant process. It has been argued that hydrology is essentially an interdisciplinary science, and only when we realise that water is the common link between Earth and social sciences, are we likely to make significant breakthroughs in understanding how water behaves in the Earths system. When developing new theories or models we need to make use of interdisciplinary skills, knowledge and experience derived from an assembly of scientific principles and tools of analysis that the hydrologist requires from various academic sources to apply equations and principles from soil science, engineering, chemistry, physics, plant physiology and climatology, to mention but a few. To integrate all these fields requires data, as despite the need to integrate across disciplines, science is founded on observations and the development of hydrological science relies greatly on the continued measurement of natural processes such as interception. The need for continued field measurements and data are highlighted by the inter-seasonal and inter-annual variability in rainfall and vegetation characteristics which cause significantly different results. There is also a need to continue collecting field data in a complex system such as the hydrological cycle in a changing environment so that changes in thresholds and processes can be understood better. Under a changing environment it becomes increasingly important to recognise not only what we are measuring, but also what we are not measuring, and a recognition that we may not even know what that is yet. Data are science, but coupled with the recognition of their limitations in scope and scale models are an important compliment to data, not a replacement for them. However, models are extremely useful as test beds for ideas and for exploring the implications of our understanding of natural systems. Models also aid in data processing and analysis, helping show up data errors and inconsistencies that might otherwise have gone unnoticed. They may also be used to demonstrate the effect of actions or non-actions to stakeholders. The most rapidly expanding use of models is for exploring scenarios that cannot be tested in the real world. Although this is a very useful application of models, it is also the most dangerous. While high level managers may appreciate the smart user interface and slick graphics and, possibly, simplistic sets of options, it can be easy to lose sight of the limitations of the processes that generated them. It is during this use of models that they may be run outside of their tested bounds, and by definition little or no data is available to constrain the scenario results. If we are going to continue to learn about environmental and hydrological processes, and improve our management we must continue to collect data. Modelling is an important accompaniment to measurement, but is not a substitute for it; science requires observations, and without that we will cease to progress in understanding the environment and hydrological processes such as interception, and therefore managing it appropriately.

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CHAPTER 9

Synthesis and recommendations for future research

1. SYNTHESIS AND RECOMMENDATIONS FOR FUTURE RESEARCH

From this focussed study on canopy and litter interception, it is hoped that the findings reported herein have dispelled any misconceptions that canopy and litter interception only constitute a small portion of total evaporation and that these processes cannot be ignored in hydrological models. Furthermore, this research makes a significant contribution towards filling the large gap that existed in South African forest hydrology and will aid in further research being undertaken on this important topic. The results shows that canopy and litter interception play an important role in the forest hydrological cycle, with between 65.7% and 76.2% of gross precipitation being available water that drains to the soil, after the losses due to canopy and litter interception at the selected study sites. This research is therefore valuable in furthering the knowledge of the canopy and litter interception processes in commercial and indigenous forests, and adds valuable knowledge on the importance of interception on water resources in the KwaZulu-Natal "mist belt" areas, and through simulation studies to South Africa as a whole. The impact of climate change on canopy interception was also considered, which is a global issue.

This study confirms that interception plays a very important role in the forest hydrological cycle. Canopy interception by *E. grandis*, *A. mearnsii* and *P. patula* accounted for a loss of 14.9%, 27.7% and 21.4% of gross precipitation respectively. Although litter interception accounts for a smaller portion of the total interception loss, it is none the less important. In this study it was found that litter interception accounted for an additional loss of 12.1% of gross precipitation by *P. patula*, and 8.5% and 6.6% for *E. grandis* and *A. mearnsii* respectively. Interception is not only reduces the amount of rainfall but is also a threshold process, as a certain amount of water is required before successive processes such as infiltration and runoff can take place. These subsequent processes can only occur once the canopy and litter storage capacities have been reached and based on the results of this study, it can be confirmed that canopy and litter storage capacity is a key factor in the control of canopy and litter interception. Although the storage capacity of the litter is much greater than that of the canopy, canopy interception is greater, highlighting that the evaporative potential of the canopy is far greater than that of the forest floor litter. On the basis of the observed experimental results and simulated results, it appears that evaporation by the canopy during rainfall events is a major component of interception loss, and is not solely dependent on the storage capacity. Conversely, litter interception is more dependent on the antecedent litter moisture and storage capacity than on the conditions during the rainfall event.

One implication of interception being a threshold process is that it causes a delay in the onset of subsequent processes, particularly infiltration. This delay may be of the order of a few seconds to minutes in cases where both the canopy and litter are near saturated or in high intensity storms. Conversely, this delay may be days or weeks in cases where a rainfall event is not large enough to

exceed the canopy storage capacity or subsequently the litter storage capacity, and therefore, only after an event large enough to satisfy the combined storage capacities of the canopy and litter will subsequent processes take place. This is highlighted in Chapter 2, where there are many events where the throughfall does not exceed the litter storage capacity and therefore there is no infiltration. This delay is also not the same for all species.

As interception reduces and delays subsequent hydrological processes differently for all species, it also determines the spatial distribution of net precipitation. Within a commercially afforested catchment such as Two Streams where there are many species and types of vegetation that all have different canopy and litter interception characteristics, the spatial distribution of net precipitation is not only different between stands, but also within the stand. It is for this reason that linear troughs were used to measure throughfall as the throughfall varies from near the trunk to the edge of the canopy, depending on the structure and water holding characteristics of the canopy. Within a commercial plantation, the spacing and management of the trees will also affect the spatial distribution of throughfall. The idea of interception being highly spatially variable was corroborated in Chapter 4, not only on a stand or catchment scale, but also on national scale depending on the location, genus/species and rainfall seasonality. Therefore, interception plays a far more significant and complex role in a catchment water balance than just as a reducer of rainfall.

The litter interception results correspond well with the few other litter interception studies in South Africa that have taken place, such as Jacobz (1987) and Jewitt (1991). However, litter thickness is highly variable in a plantation and a mean thickness per stand was used. Therefore, like the canopy interception results, the litter interception results should be used with caution when upscaling. It would be unwise to consider these results as representative across a wider geographic area, as canopy interception results in areas where there are more events of larger magnitude and intensity would probably be lower.

As this study confirms that canopy and litter interception can play a significant role in the water balance of a forested catchment this component should not be ignored for water resources planning purposes. To account for canopy and litter interception loss for water resources planning, models that are easily parameterised and that can make use of readily available data would improve and aid in decision making. Drawing on both field data collected at Two Streams between April 2008 and March 2011 and laboratory data, models to represent these processes were developed and verified (*cf.* Chapter 3). The models developed were able to represent the interception process and therefore values with a good degree of accuracy. Historical data from September 1998 to March 2011 were input into the models to determine if the interception results would vary over the 13 year period. It was found that there was only a small difference between the modelled results from April 2008 to March 2011 and September 1998 to March 2011.

A shortcoming of the approach used to model litter interception is that the model is dependent upon the accuracy of the canopy interception model. If the throughfall or canopy interception is modelled poorly, then the input into the litter interception model will induce an error. The observed results for the water that drains to the soil, which is the "useable water", is a good indicator of how the canopy and litter interception models performed as an integrated whole. This is because the water that drains to the soil is measured as a separate entity and is not derived from a mass balance of the other measured components (i.e. gross precipitation and throughfall), as is the case with litter interception. Therefore, if the canopy and litter models did not perform well, then the modelled water that drained to the soil would not correspond well to the observed results. While modelling is vitally important in effective water resources management, if we are going to continue to learn about environmental and hydrological processes, and improve our management we must continue to collect data. Modelling is an important accompaniment to measurement, but is not a substitute for it; science requires observations, and without that we will cease to progress in understanding the environment and hydrological processes such as interception, and therefore managing it appropriately.

It is suggested that the "variable storage Gash" canopy interception model developed during the course of this study could be applied for national scale studies (*cf*. Chapter 4) as it is based on easily measured input parameters that are not site specific. However, although the litter interception model structure is sound and transferable, it is based on a site specific drying curve which are not transferable to other sites as it is site, species and age dependant. Such drying curves are easily derived from litter samples and further studies to generate national litter interception characteristics are a logical way forward.

The problems of modelling canopy interception on a catchment scale have received remarkably little attention and even less on a national scale in South Africa. To address this shortcoming, the "variable storage Gash model" was used to model canopy interception for the three most common commercial forestry genera in South Africa, (*viz., Eucalyptus, Acacia* and *Pinus*) at a national scale using data from the South African quinary catchment database for all the catchments with a mean annual precipitation greater than 600 mm.annum^{-1} (*cf*. Chapter 4). The results of the study show that canopy interception is highly variable depending on the genus and rainfall seasonality. Canopy interception was shown to range between 10 and 40% of gross precipitation or between 100 and 300 mm per year. The mean annual canopy interception loss per rainday was found to be between 1.0 mm and 3.0 mm.rainday^{-1} for *Eucalyptus, Acacia* and *Pinus* genera, which is consistent with other South African researchers including Schulze *et al*., 1978; Dye and Versfeld, 1992, who suggest that canopy interception ranges between 0.5 to 3.5 mm.rainday^{-1}.

Having gained an understanding and quantified canopy and litter interception in exotic commercial forest plantations (*cf*. Chapters 2 and 3), the study was extended to an indigenous *Podocarpus henkelii*

stand which was compared to an exotic *P. patula* stand (*cf*. Chapter 5). It was found that the canopy interception by *P. henkelii* and *P. patula* was 29.8% and 22.1% respectively. The litter interception by *P. henkelii* and *P. patula* was found to be 6.2% and 10.7% respectively. As well as interception measurements, transpiration was also measured in the *P. henkelii* and *P. patula* stands so that the water use efficiency could be determined. If only the productive green water use (transpiration) is considered, then the water use efficiency for *P. henkelii* and *P. patula* was found to be 7.14 g.mm^{-1} and 25.21% respectively. However, from a water management perspective it is important to consider the total green water use efficiency (transpiration + interception), which reveals a significantly lower water use efficiency of 3.8 g.mm^{-1} and 18.8g.mm^{-1} for *P. henkelii* and *P. patula* respectively.

In order to obtain estimates of LAI and canopy storage capacity of both exotic forest plantations and indigenous forests, remote sensing technology has become a valuable tool for use in modelling/estimating canopy interception and provides a potential solution to effectively monitor the spatial and temporal variability of LAI. Thus, the ability to remotely predict LAI and eventually water use over a large area is sought after by various stakeholders including the forestry industry, and water resources managers and planners. Due to the proposed future availability and accessibility of hyperspectral sensors in southern Africa there is likely to be an increased interest in using high spectral resolution data for a wide variety of environmental applications. Methods to quantify canopy interception typically require LAI as an input into the various equations and process models that are applied. Using Hyperion hyperspectral imagery and three vegetation indices, namely the normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI) and Vogelmann index 1, the LAI for Euc*alyptus, Pinus* and *Acacia* genera at a site where they all grow in close proximity to each other was estimated (*cf*. Chapter 6). Of the three vegetation indices used in this study, it was found that the Vogelmann index 1 was the most robust index with an R^2 and root mean square error (RMSE) values of 0.7 and 0.3 respectively.

In the past there has been a reluctance to use remote sensing for hydrological applications by the hydrology community at large and in southern Africa in particular. This can be attributed to reasons such as, the unavailability to the relevant hardware and software, lack of knowledge of the application of remote sensing techniques and the reluctance to change conventional and well established methods. However, now in its 4th decade, the use of earth observation data in water resources is becoming increasingly important. The results obtained from this study show that the use of remote sensing for the estimation of LAI is possible with a relatively high degree of accuracy. The potential to use remote sensing to estimate LAI on a large scale and link this to water resources studies at various scales is one of many possible applications. Although remote sensing approaches, once verified may reduce the amount of field work needed, ground truthing cannot be excluded completely without inducing high levels of uncertainty on the outcome of the task. Although the results obtained in this

study indicate that remote sensing techniques can be used in interception studies, further fieldwork to verify the model is needed.

Climate change has become a global issue that cannot be ignored. As forests are critically linked to climate, the impact of climate change on canopy interception was investigated (*cf*. Chapter 7). The CABALA model was used to model LAI and transpiration of *Eucalyptus grandis* and *Pinus patula* under 9 different climate change scenarios, including changes in temperature, rainfall and atmospheric CO_2. Results show that LAI may increase by as much as 24% and transpiration may decrease by as much as 13%, depending on the scenario, location and tree species. Using the "variable storage Gash model" to simulate canopy interception under these scenarios, despite changes in LAI it was found that canopy interception does not change greatly, leading to the conclusion that under climate change conditions, canopy interception may not become a more dominant component of the hydrological cycle than it currently is due to the complex interactions between climatic/atmospheric and physiological changes. However, the results show that it remains an important consideration for water resources management both currently and in the future.

Although this focussed interception study has addressed some important knowledge gaps regarding the importance of interception in South Africa, it has also raised several issues which require further investigation. In conclusion, the following recommendations for future research have been identified:

1. For the importance of interception in South Africa to be more fully understood, canopy and litter interception studies should be undertaken over a wider range of bioclimatic areas/zones, vegetation types and tree ages.

2. The litter interception model is reliant on a site specific drying curve. Therefore, the development of a litter interception model that is not site specific, but rather uses physically controlling parameters such as temperature, humidity and litter thickness should be investigated.

3. Therefore, a study on the difference between the above and below canopy climate variables driving canopy and litter interception respectively should be undertaken.

4. To study the contribution of fog interception in the mist-belt areas of South Africa.

5. Forestry usually takes place where the baseline vegetation is grassland. Therefore, the interception by grasslands is required to determine the difference in evaporative losses and establish a baseline water use.

6. Sugarcane is a candidate SFRA and has a high LAI. However, few, if any sugarcane interception studies have been undertaken. Therefore, it is important to measure its canopy interception to gain a better understanding of the total evaporation from sugarcane.
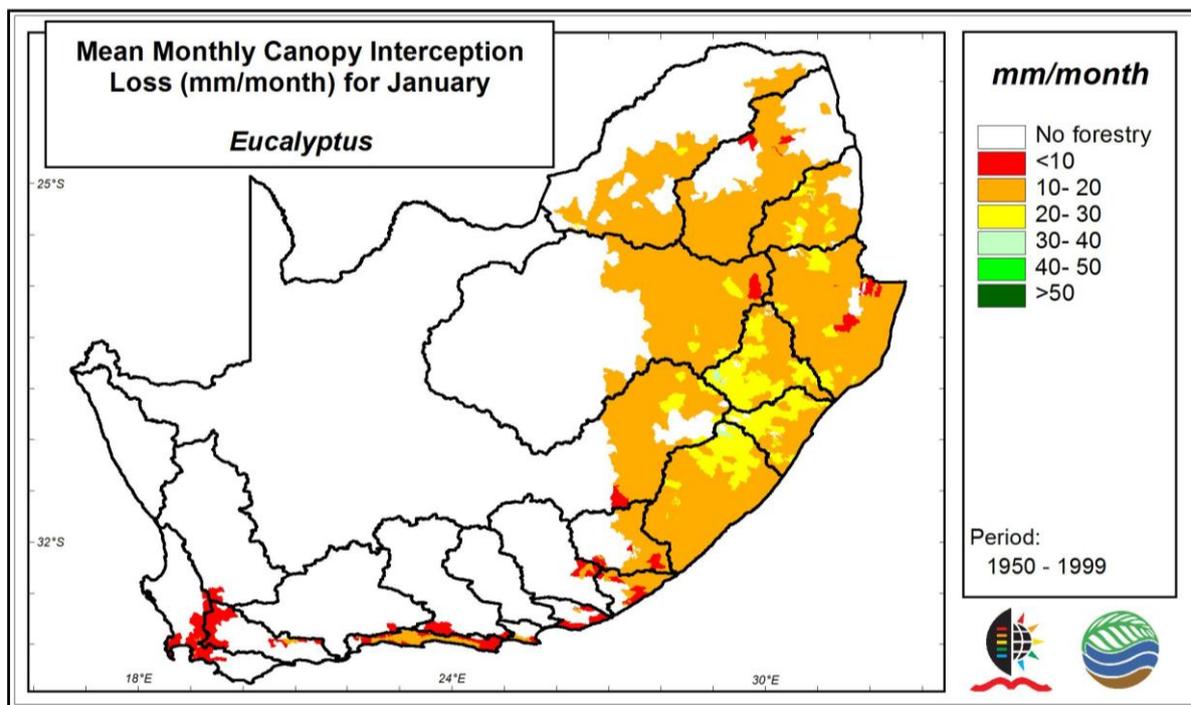
Figure A1   Mean canopy interception loss in January for *Eucalyptus* in South Africa.
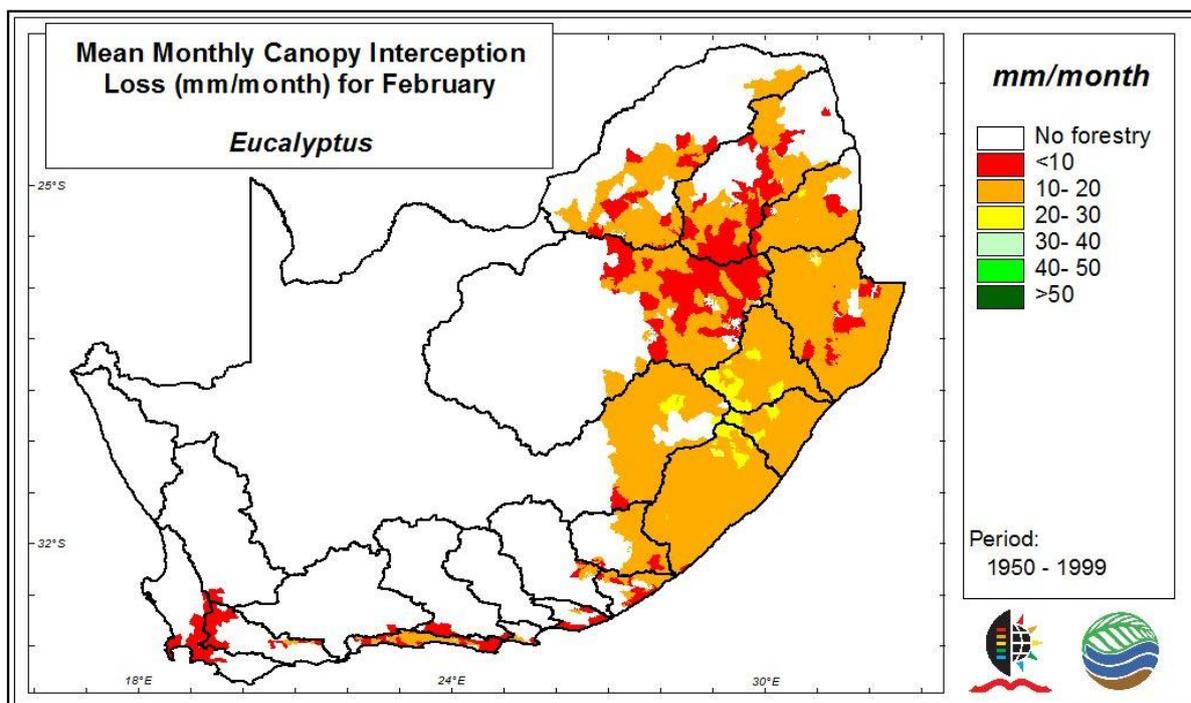
Figure A2   Mean canopy interception loss in February for *Eucalyptus* in South Africa.
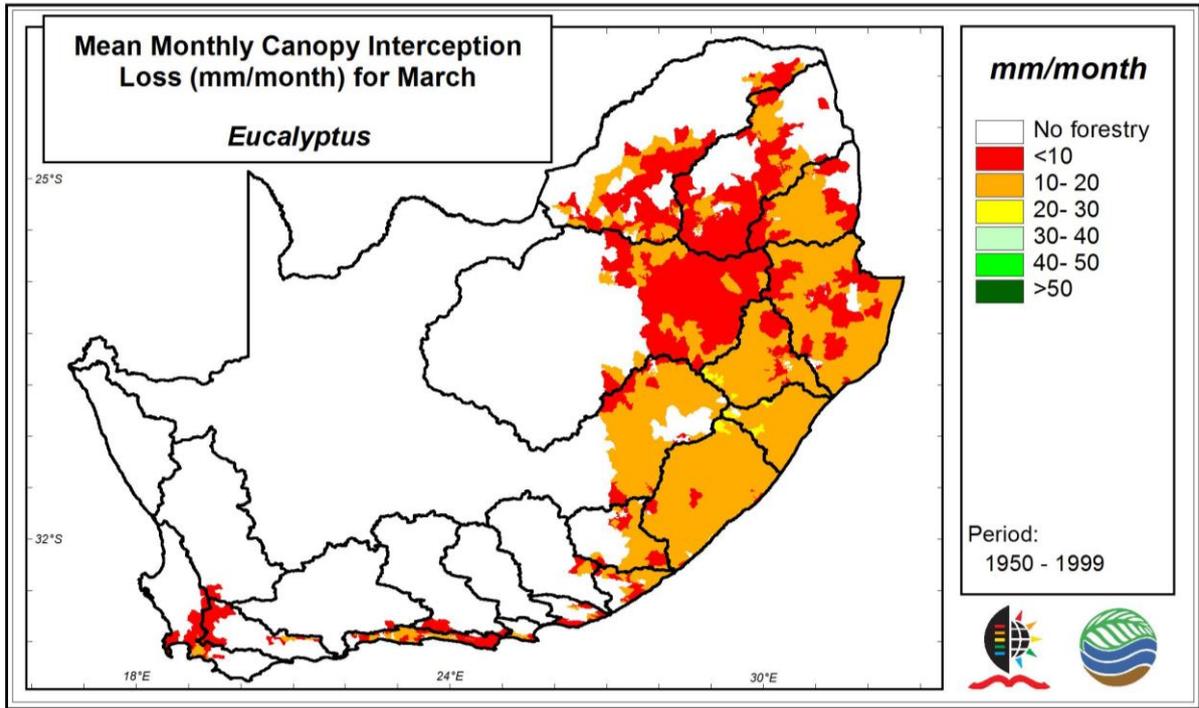
Figure A3   Mean canopy interception loss in March for *Eucalyptus* in South Africa.
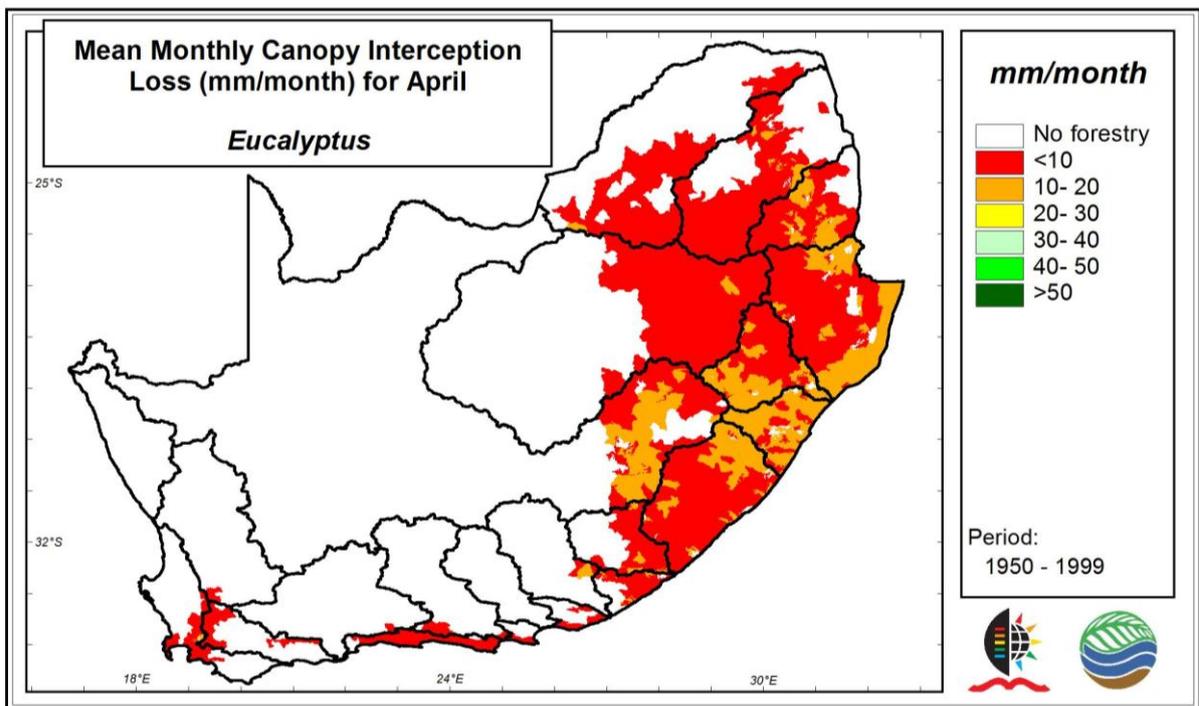
Figure A4   Mean canopy interception loss in April for *Eucalyptus* in South Africa.
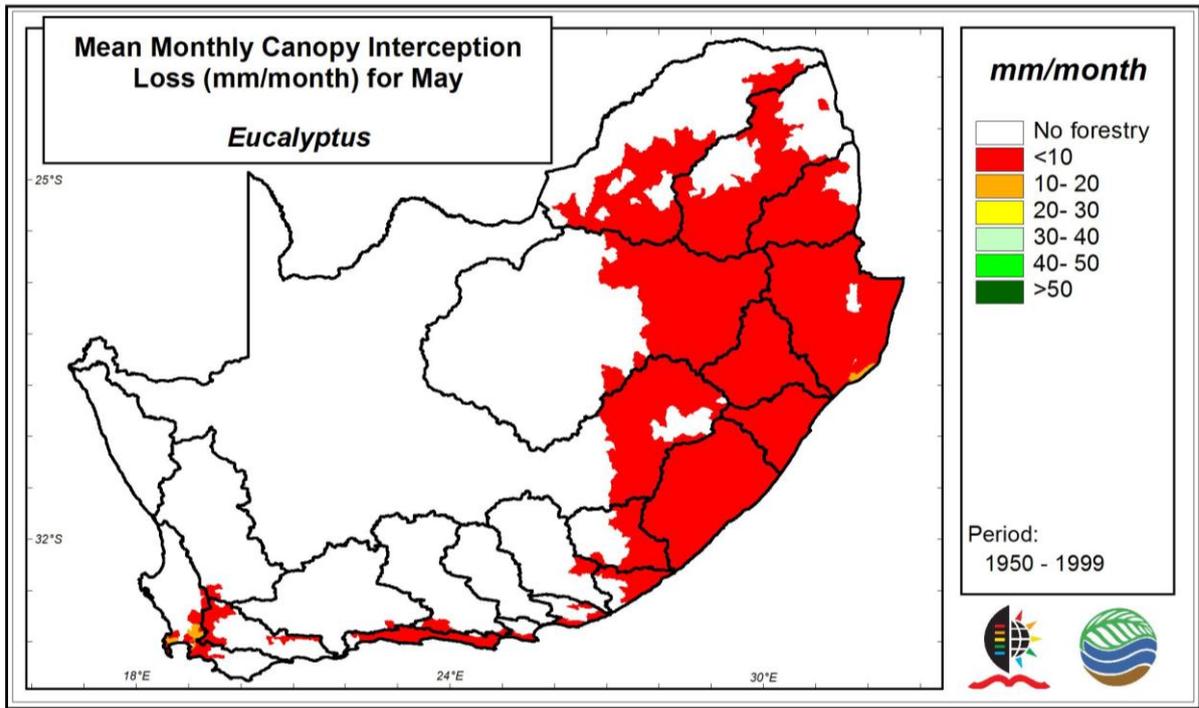
Figure A5   Mean canopy interception loss in May for *Eucalyptus* in South Africa.
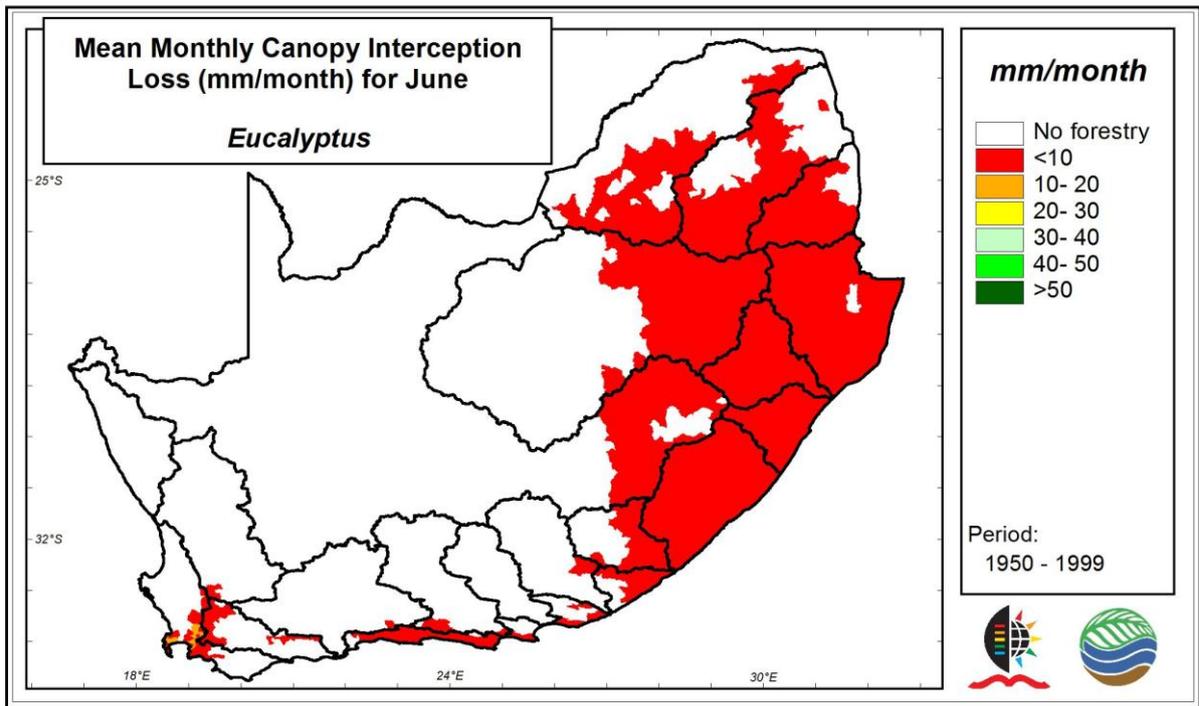
Figure A6   Mean canopy interception loss in June for *Eucalyptus* in South Africa.
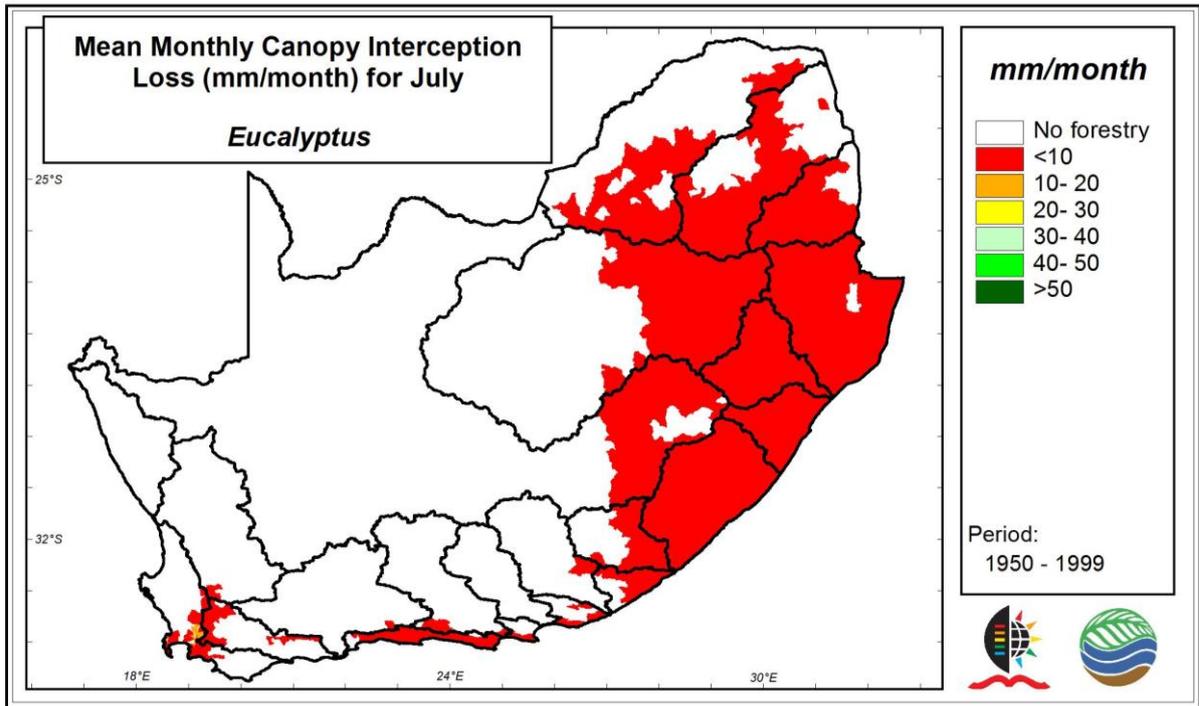
Figure A7   Mean canopy interception loss in July for *Eucalyptus* in South Africa.
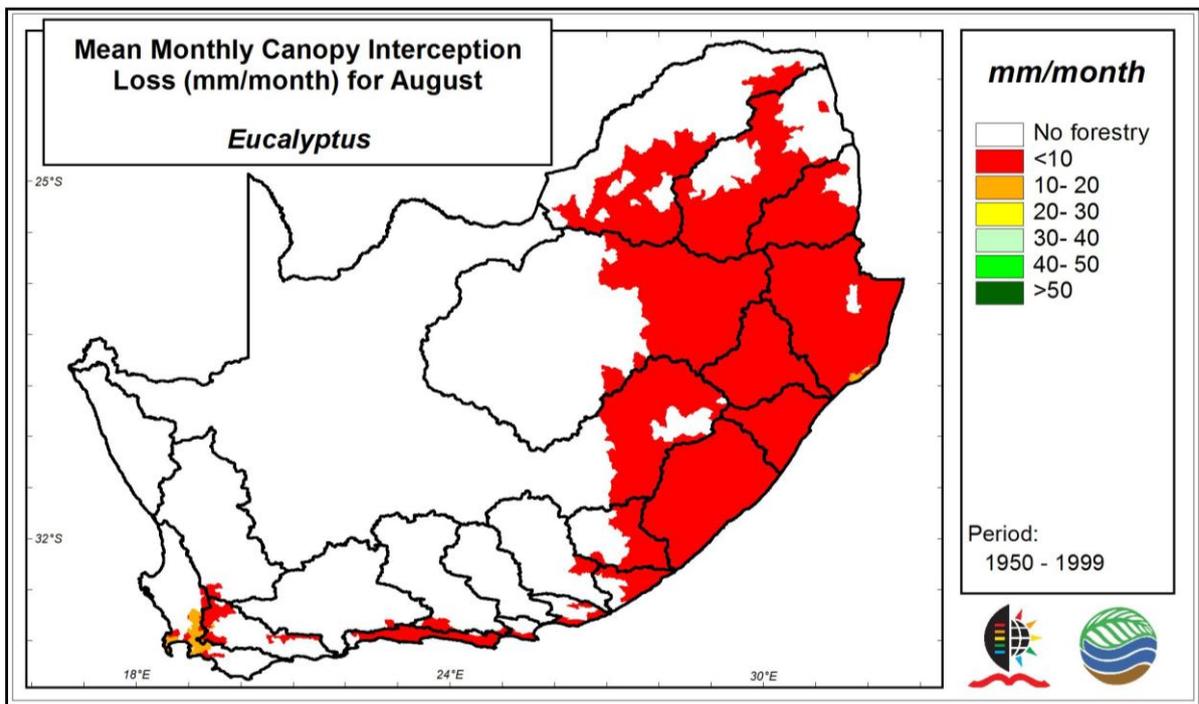
Figure A8   Mean canopy interception loss in August for *Eucalyptus* in South Africa.
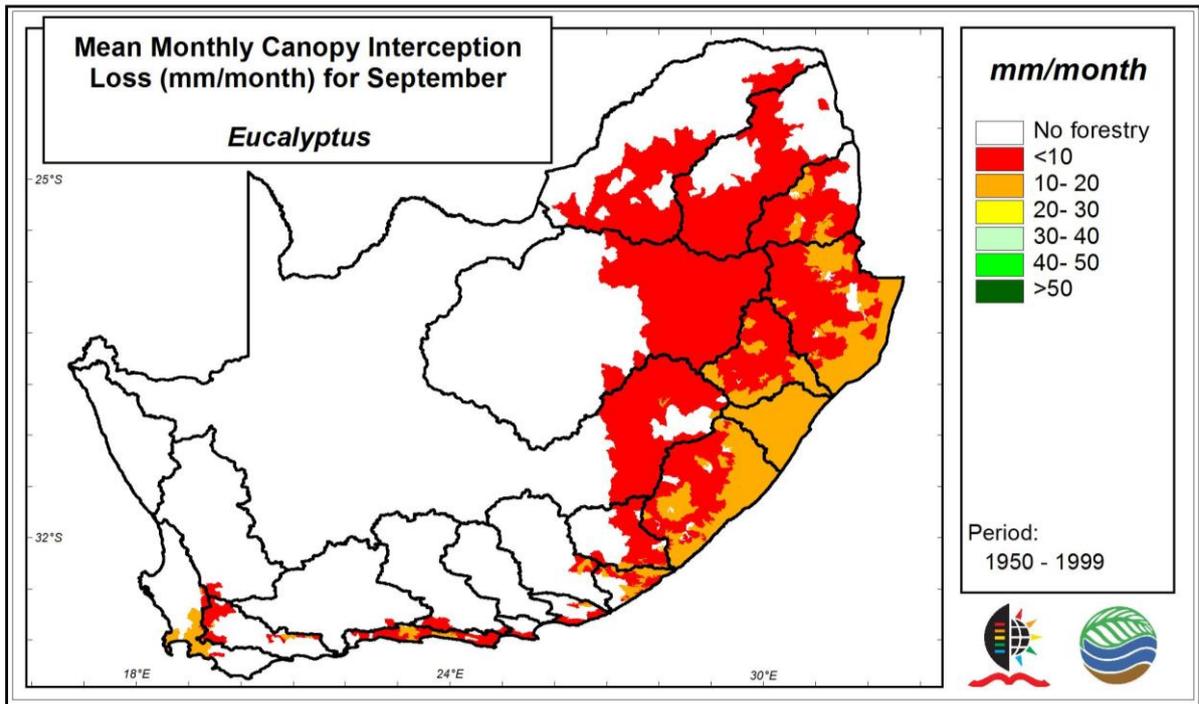
Figure A9   Mean canopy interception loss in September for *Eucalyptus* in South Africa

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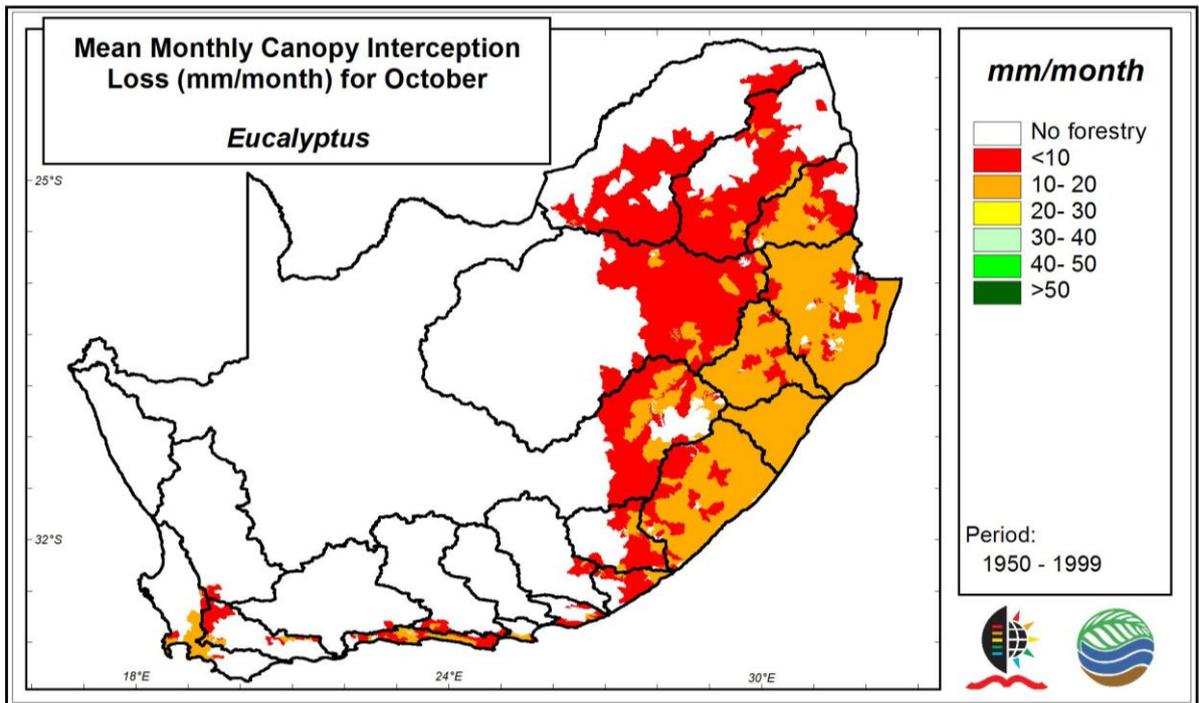
Figure A10   Mean canopy interception loss in October for *Eucalyptus* in South Africa.

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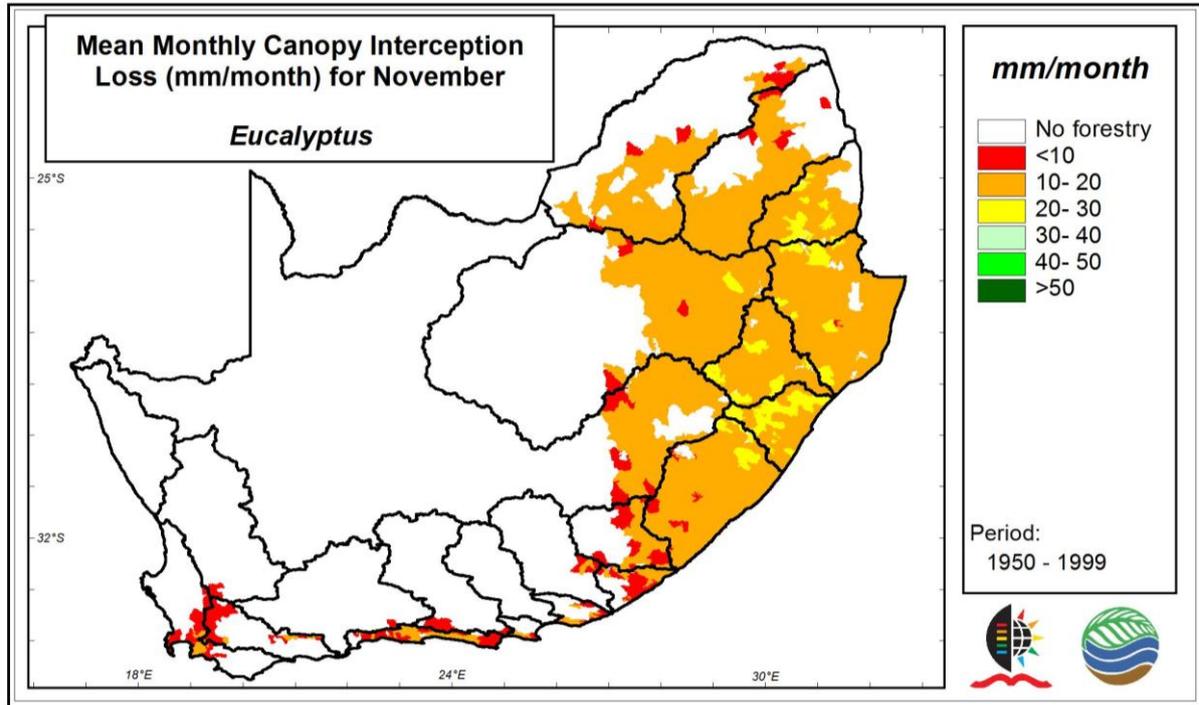
Figure A11   Mean canopy interception loss in November for *Eucalyptus* in South Africa.
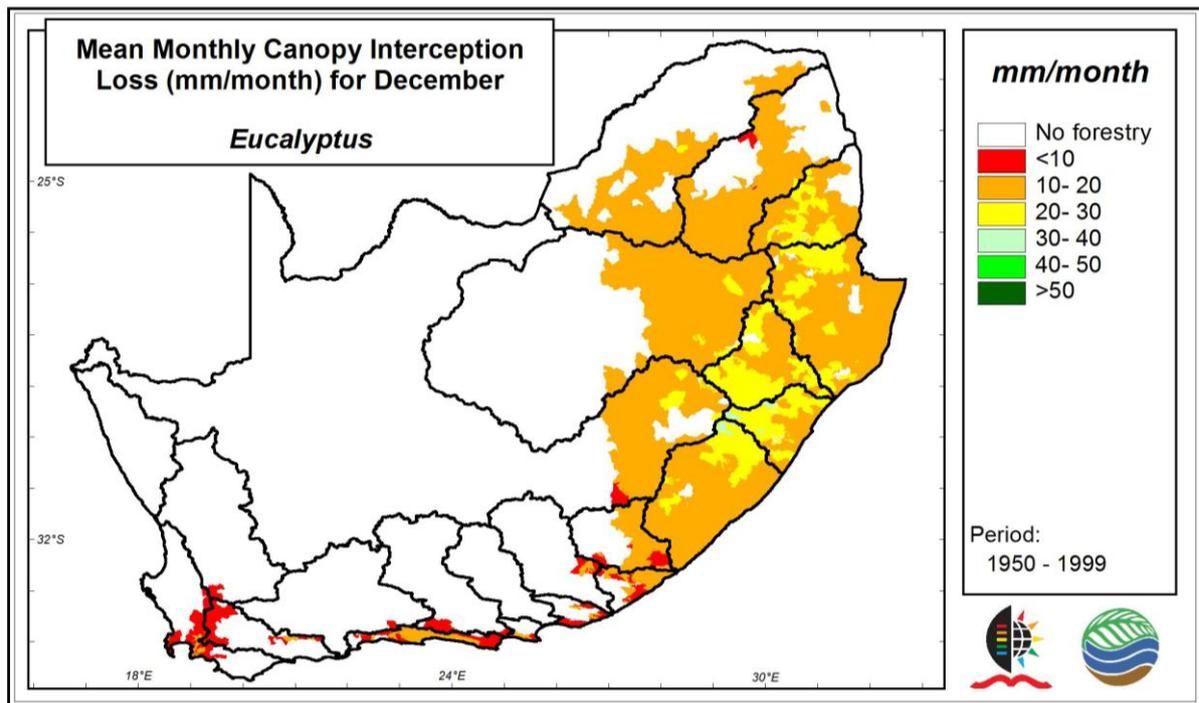
Figure A12   Mean canopy interception loss in December for *Eucalyptus* in South Africa.
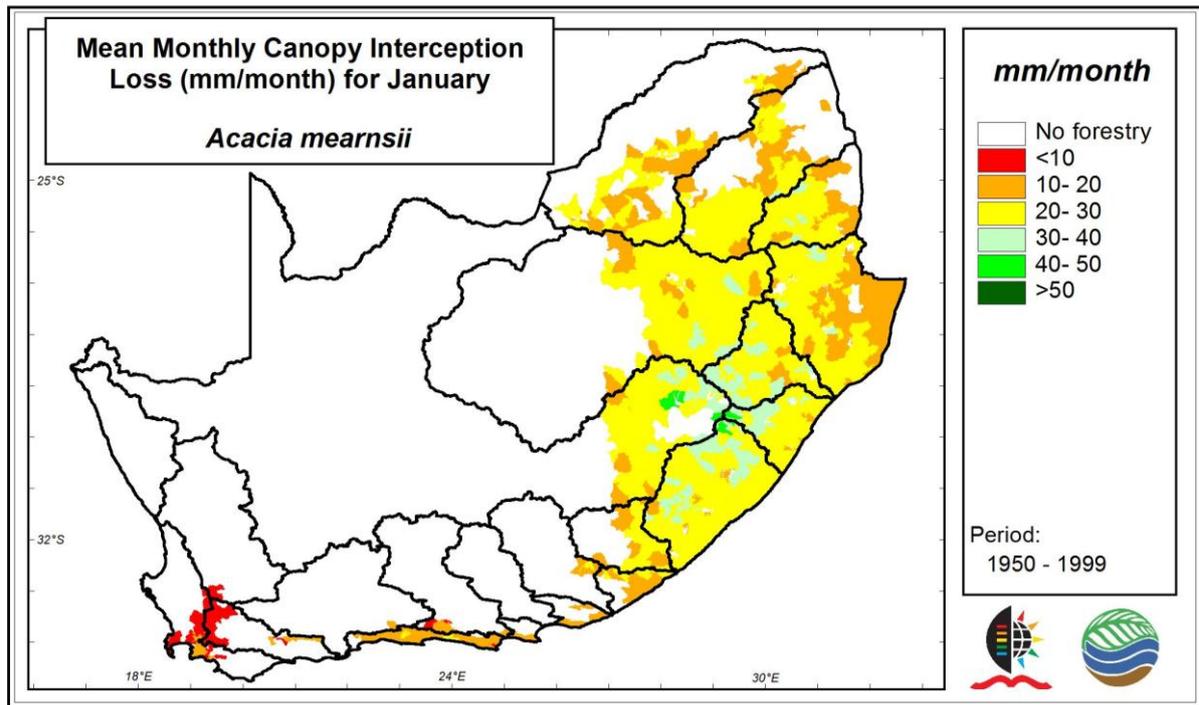
Figure B1   Mean canopy interception loss in January for *Acacia mearnsii* in South Africa.
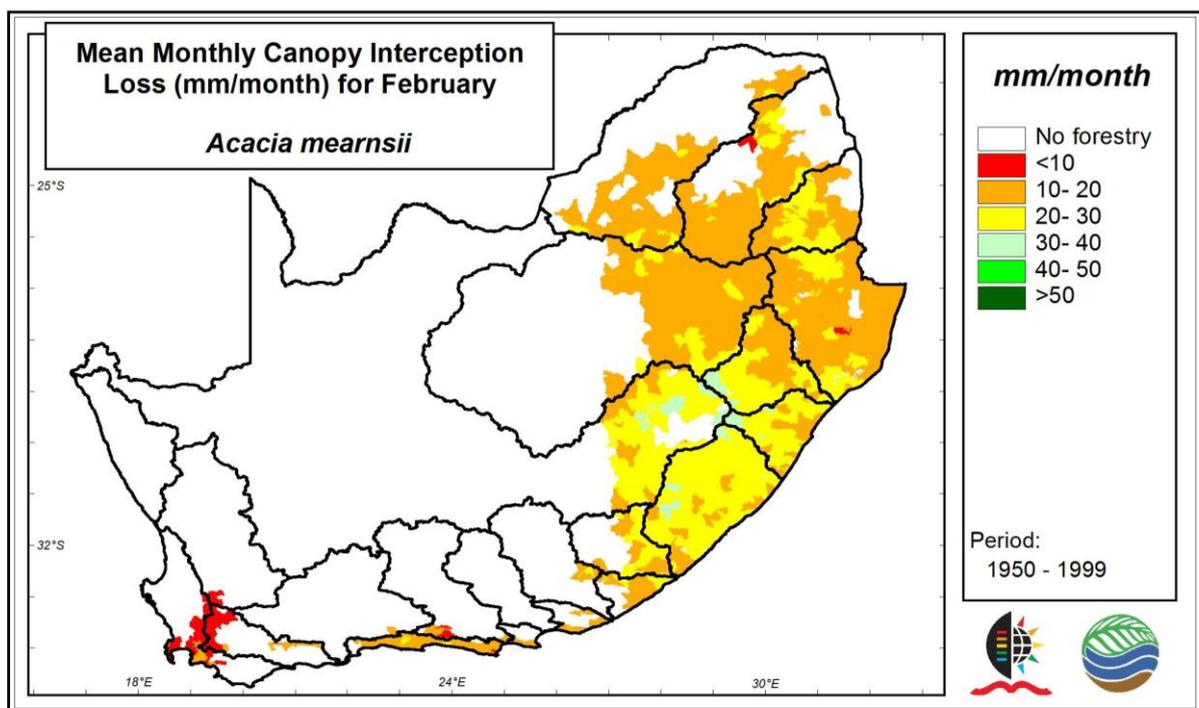
Figure B2   Mean canopy interception loss in February for *Acacia mearnsii* in South Africa.
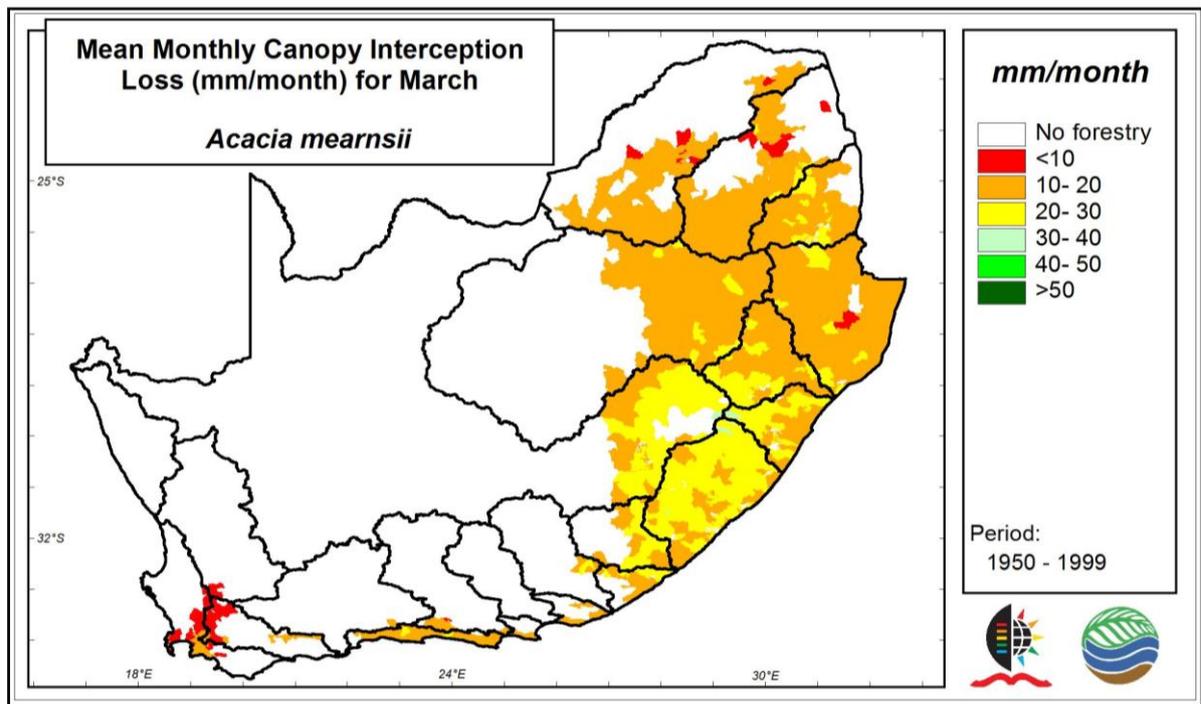
Figure B3   Mean canopy interception loss in March for *Acacia mearnsii* in South Africa.
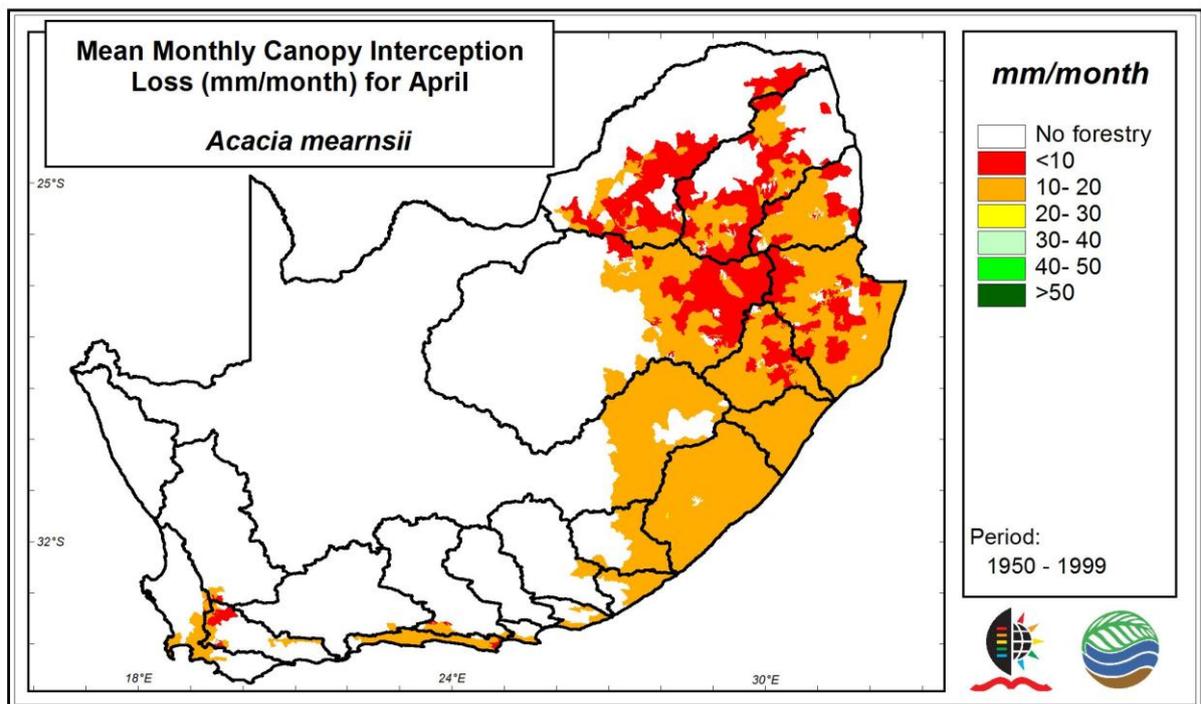
Figure B4   Mean canopy interception loss in April for *Acacia mearnsii* in South Africa.
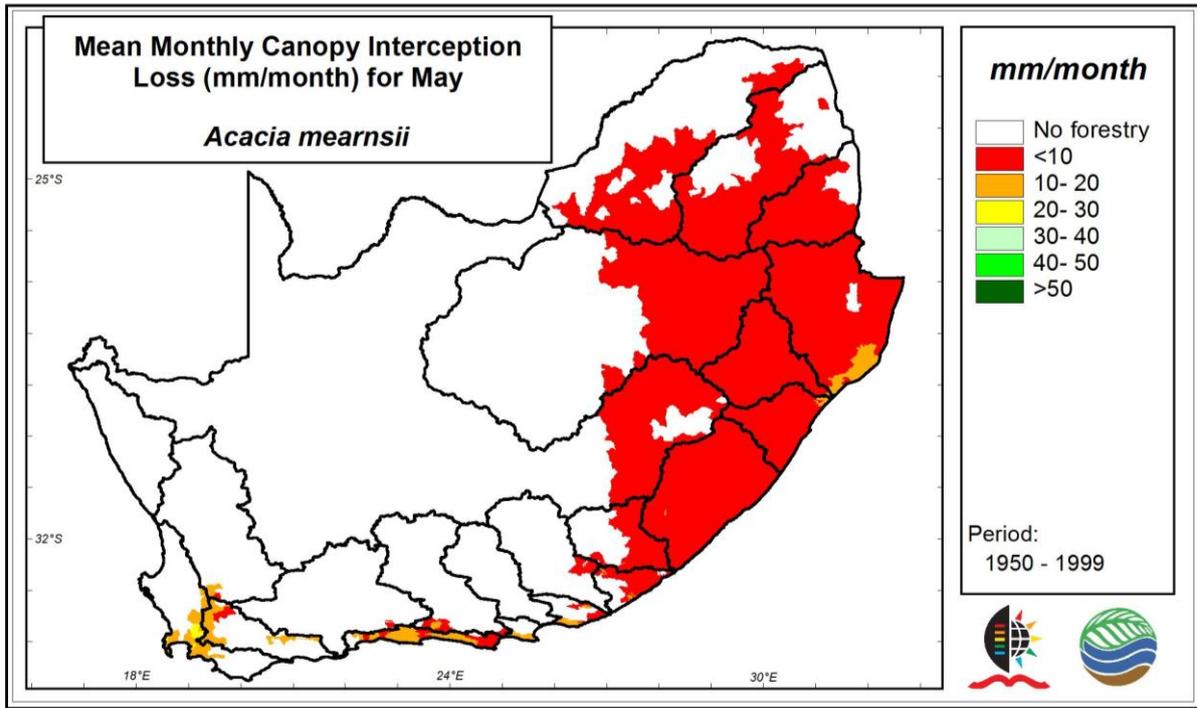
Figure B5   Mean canopy interception loss in May for *Acacia mearnsii* in South Africa.
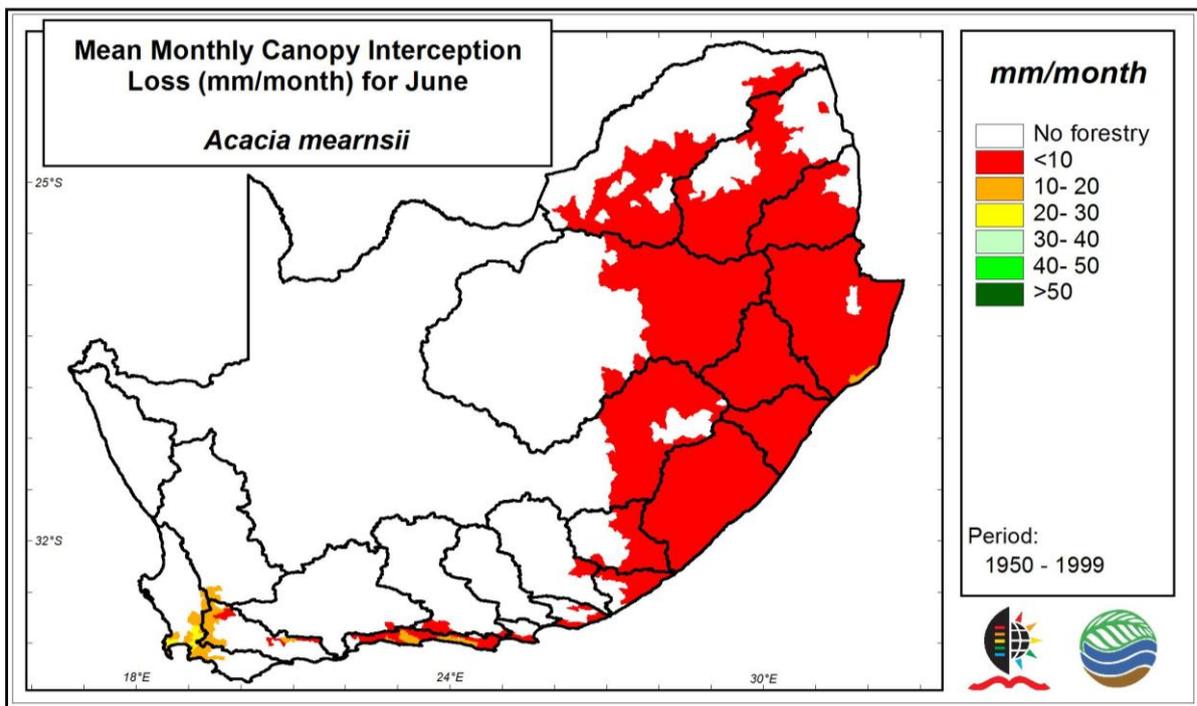
Figure B6   Mean canopy interception loss in June for *Acacia mearnsii* in South Africa.
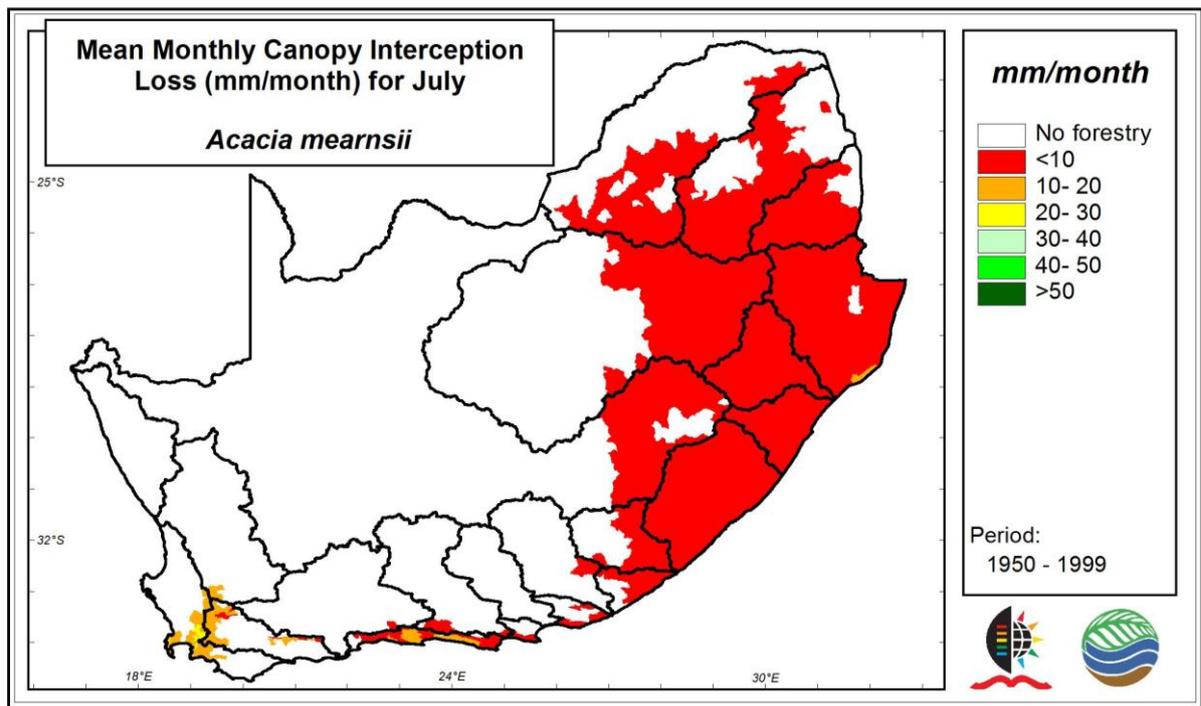
Figure B7   Mean canopy interception loss in July for *Acacia mearnsii* in South Africa.
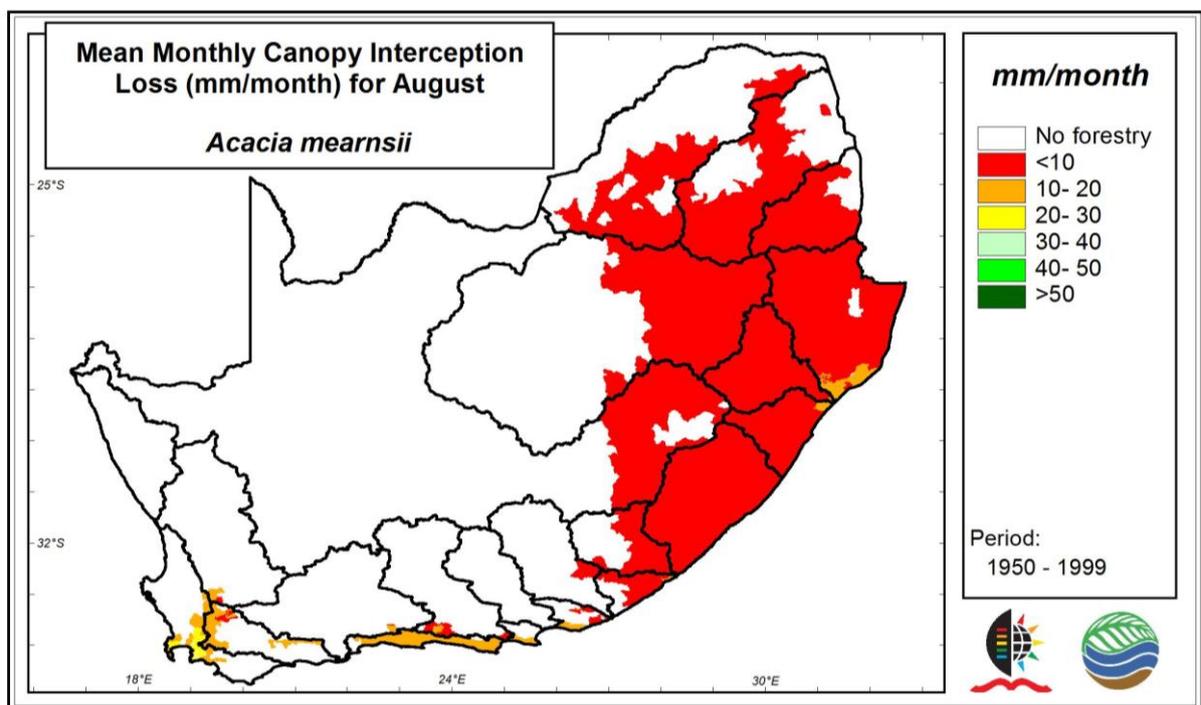
Figure B8   Mean canopy interception loss in August for *Acacia mearnsii* in South Africa.
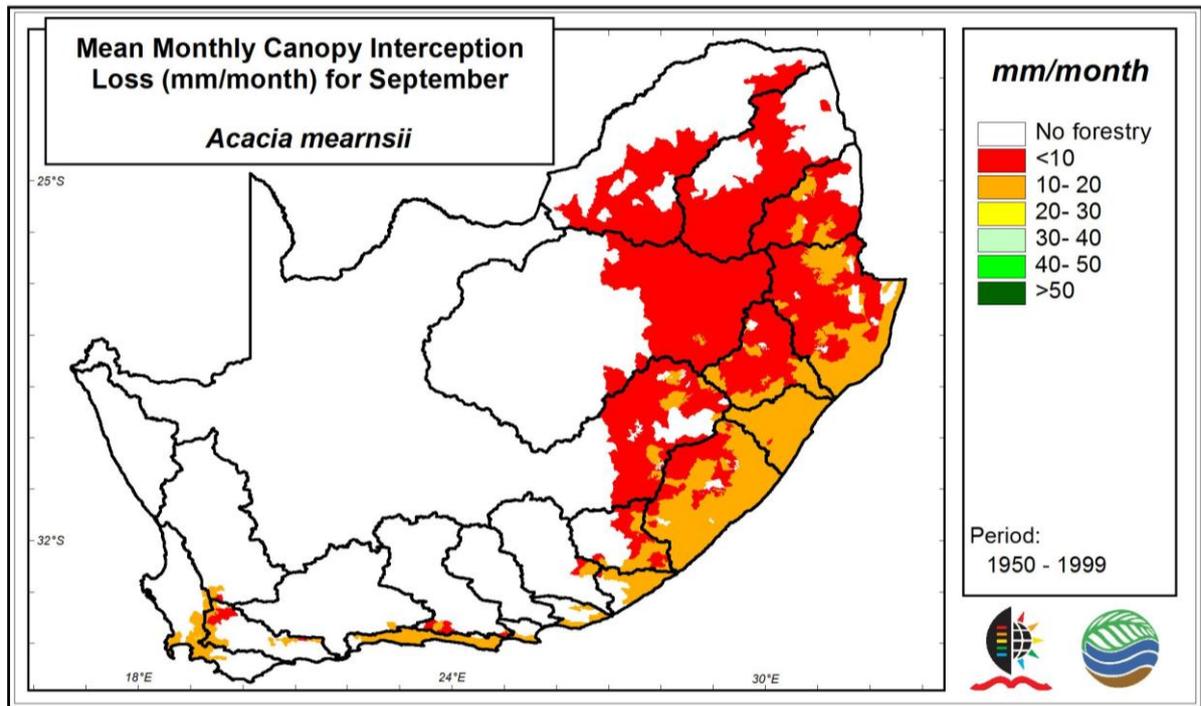
Figure B9   Mean canopy interception loss in September for *Acacia mearnsii* in South Africa.
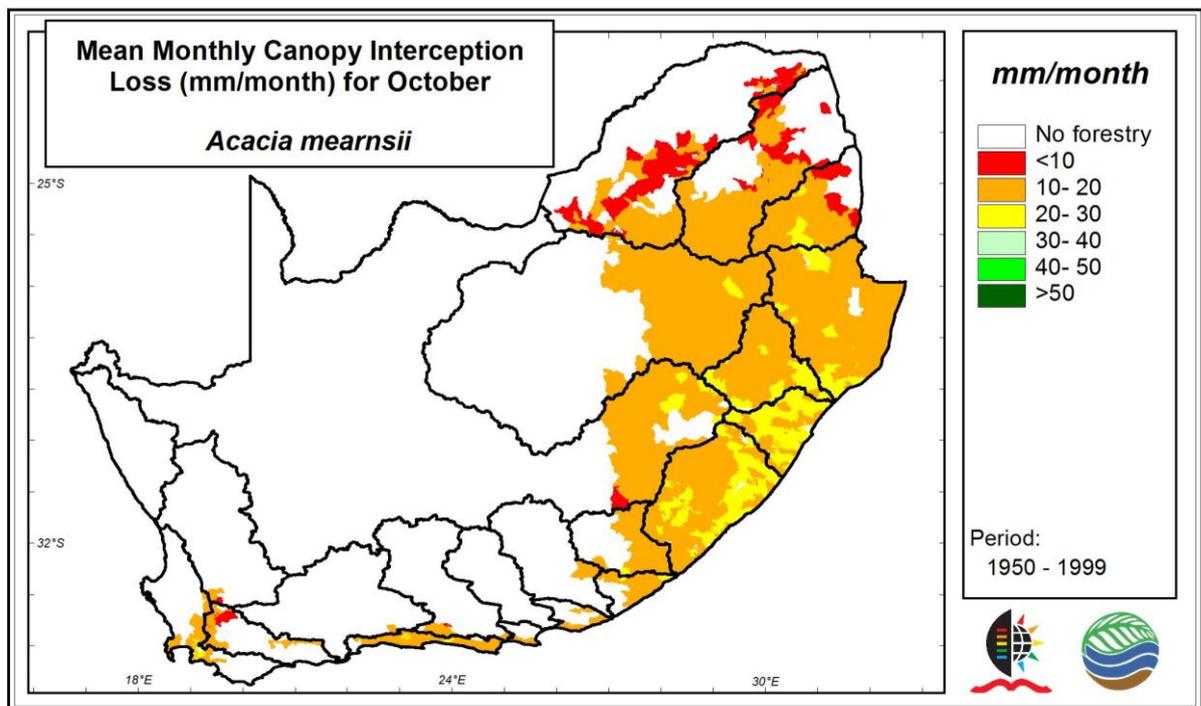
Figure B10   Mean canopy interception loss in October for *Acacia mearnsii* in South Africa
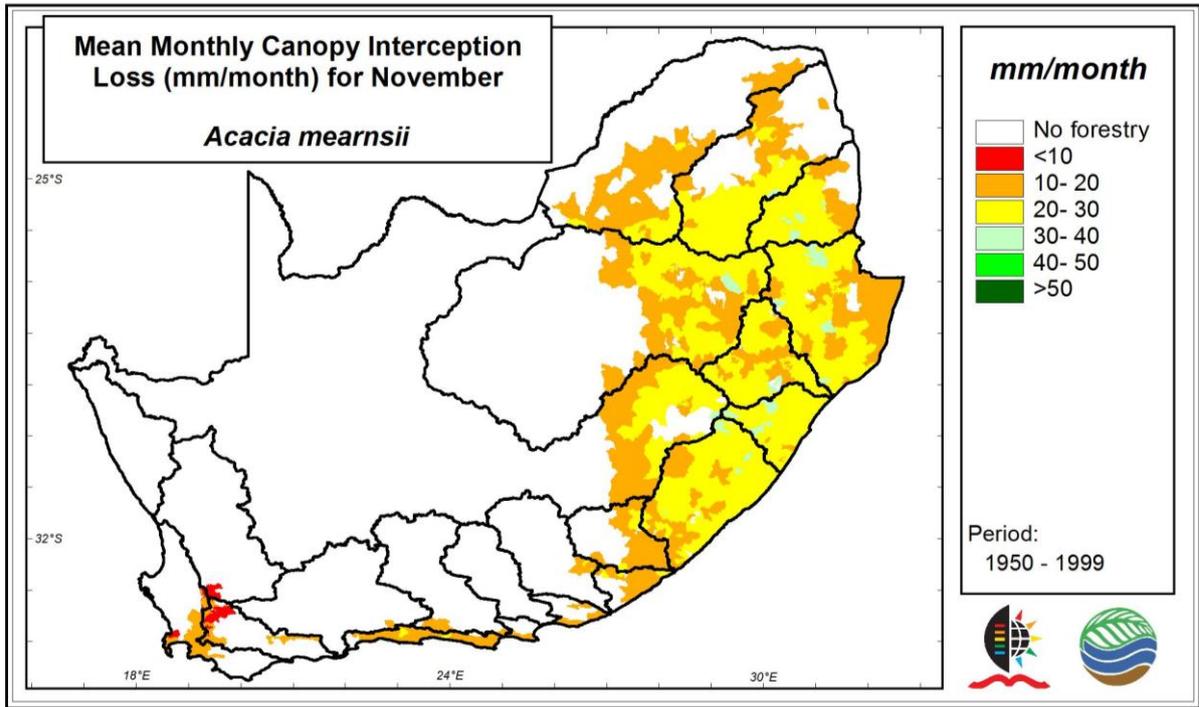
Figure B11   Mean canopy interception loss in November for *Acacia mearnsii* in South
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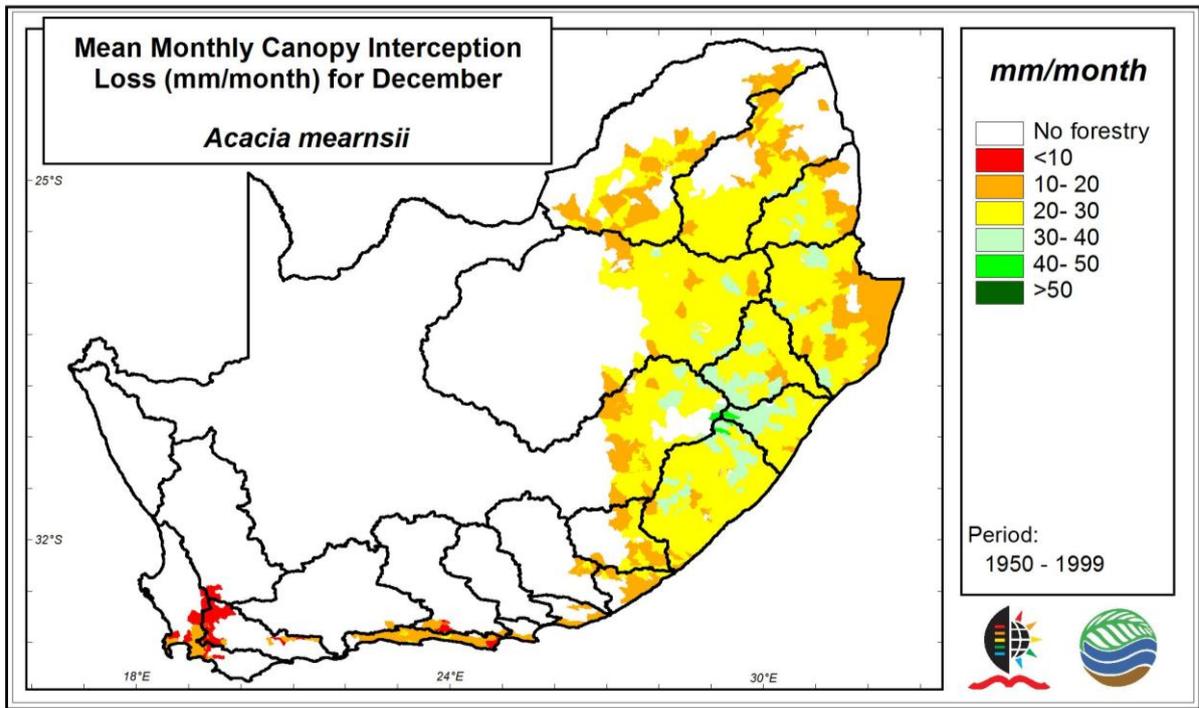
Figure B12   Mean canopy interception loss in December for *Acacia mearnsii* in South
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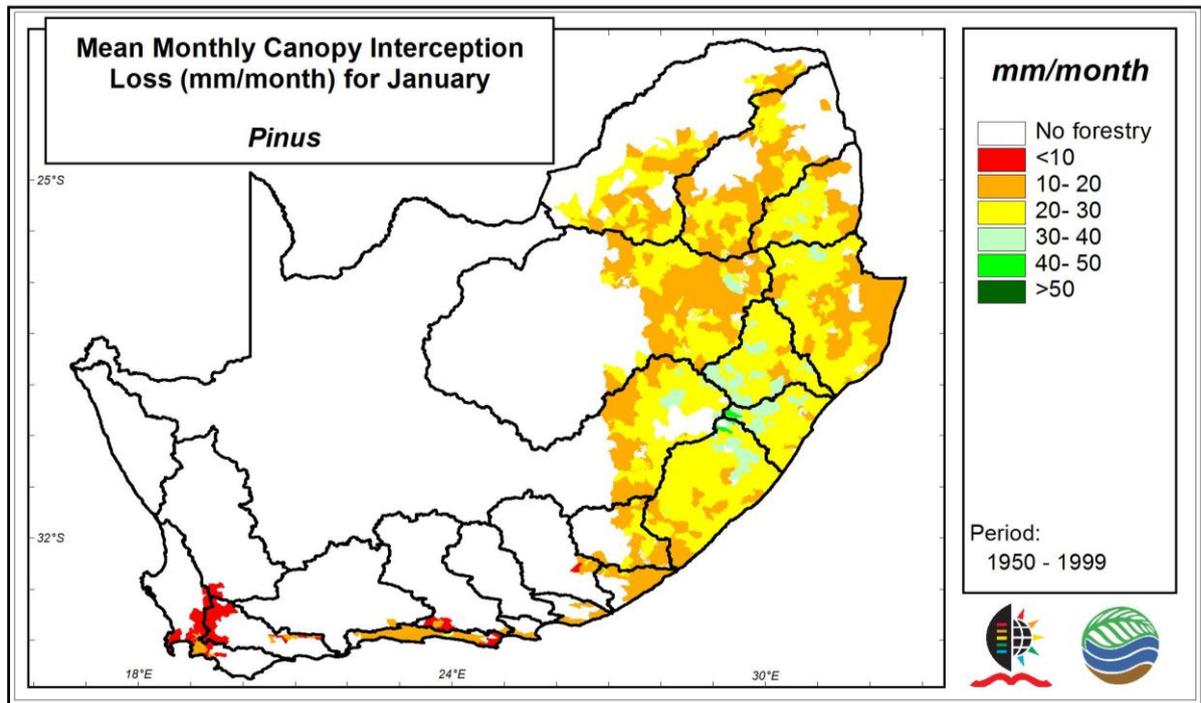
Figure C1   Mean canopy interception loss in January for *Pinus* in South Africa.
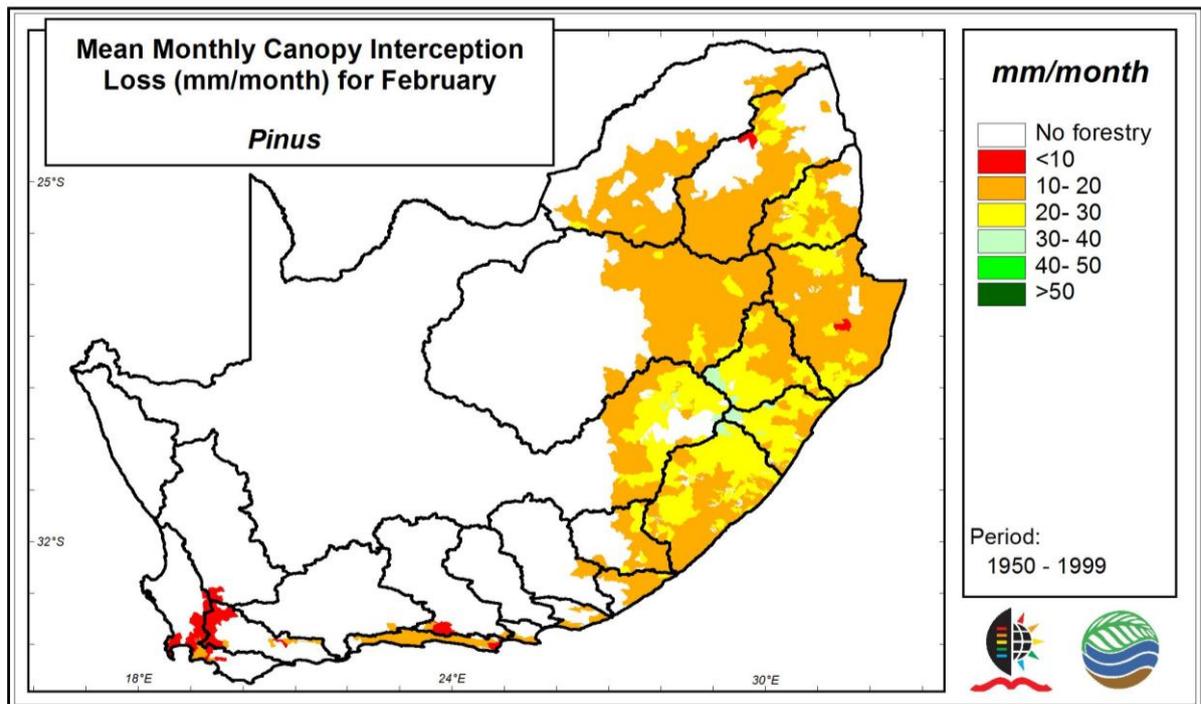
Figure C2   Mean canopy interception loss in February for *Pinus* in South Africa.
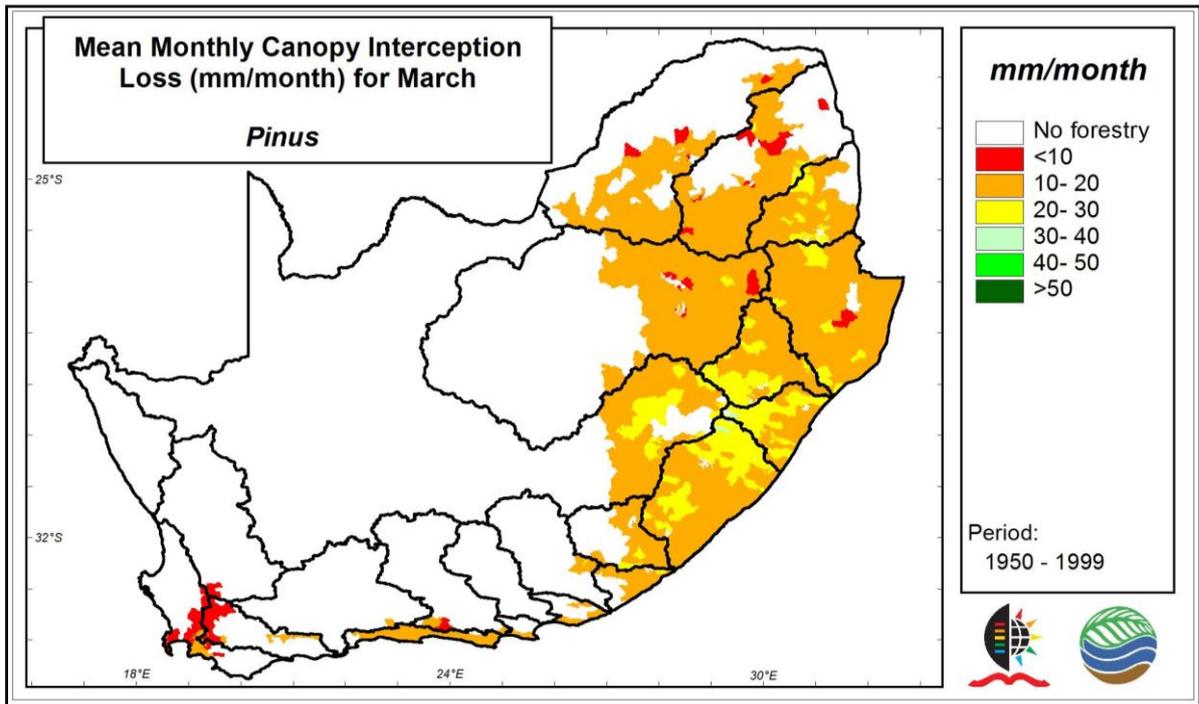
Figure C3   Mean canopy interception loss in March for *Pinus* in South Africa.
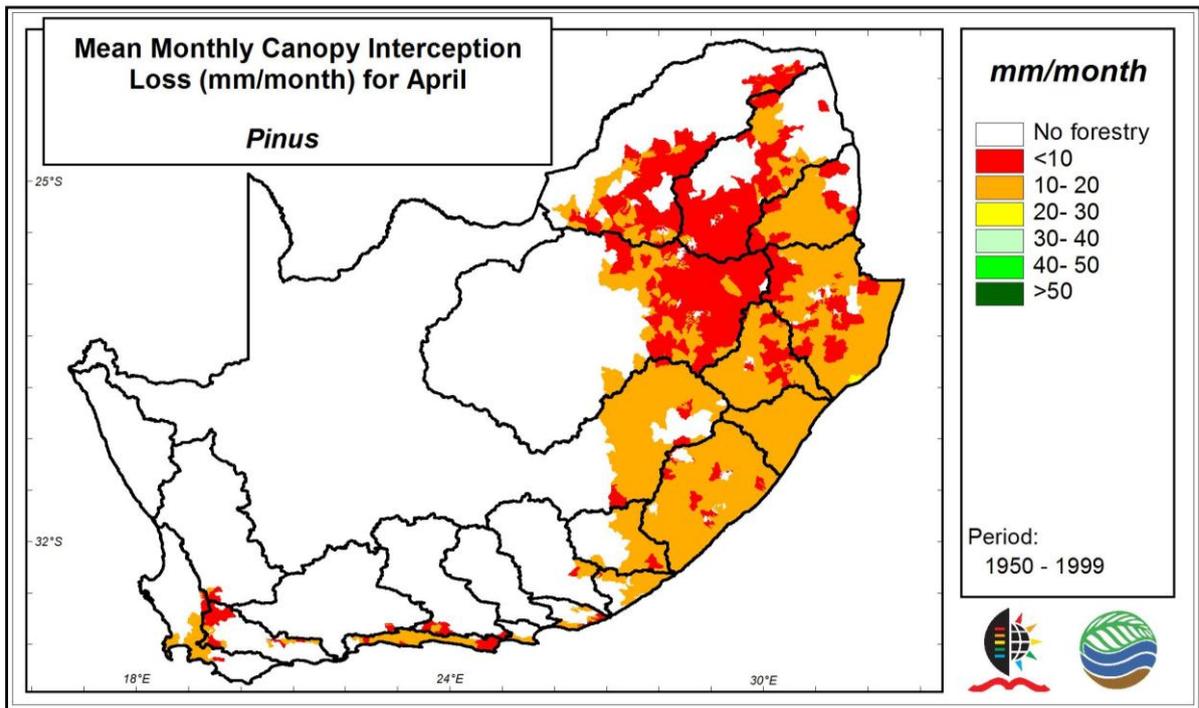
Figure C4   Mean canopy interception loss in April for *Pinus* in South Africa.
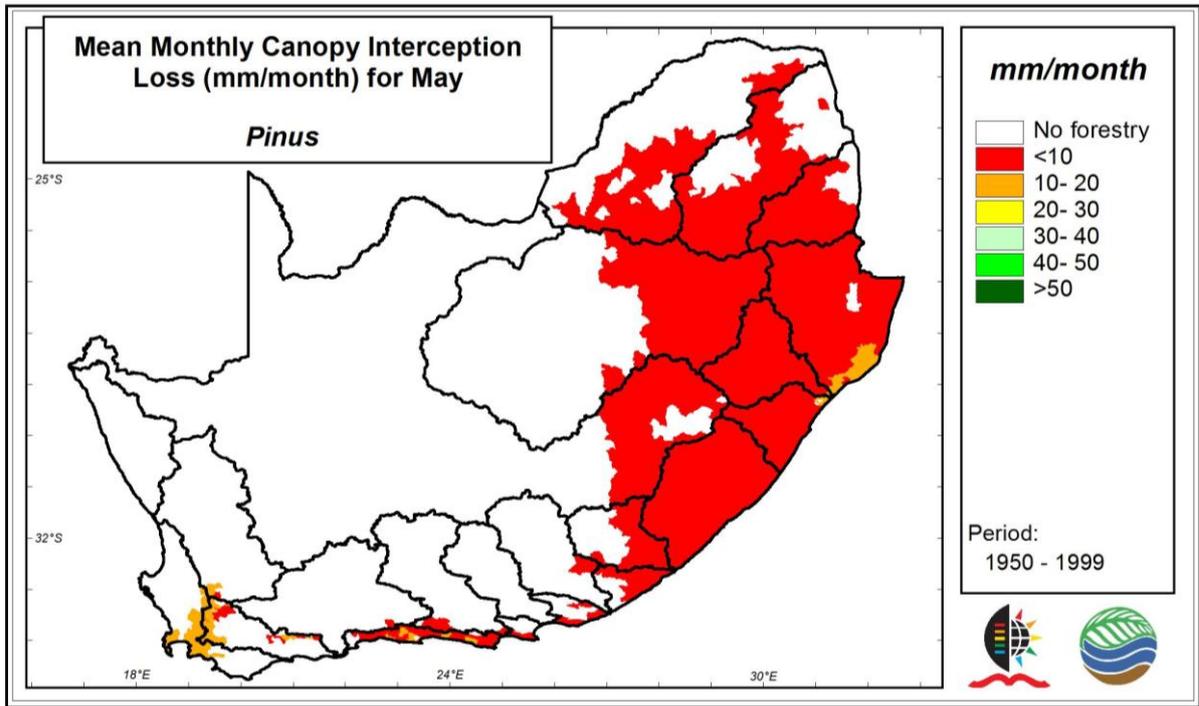
Figure C5   Mean canopy interception loss in May for *Pinus* in South Africa.
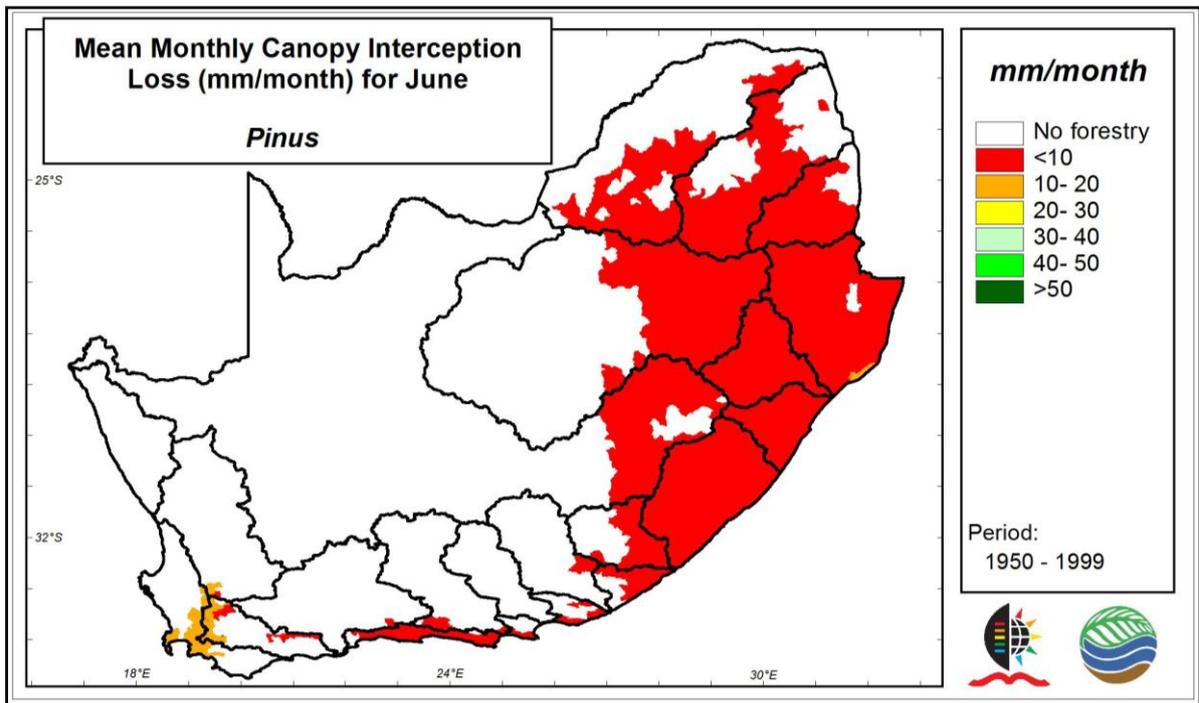
Figure C6   Mean canopy interception loss in June for *Pinus* in South Africa.
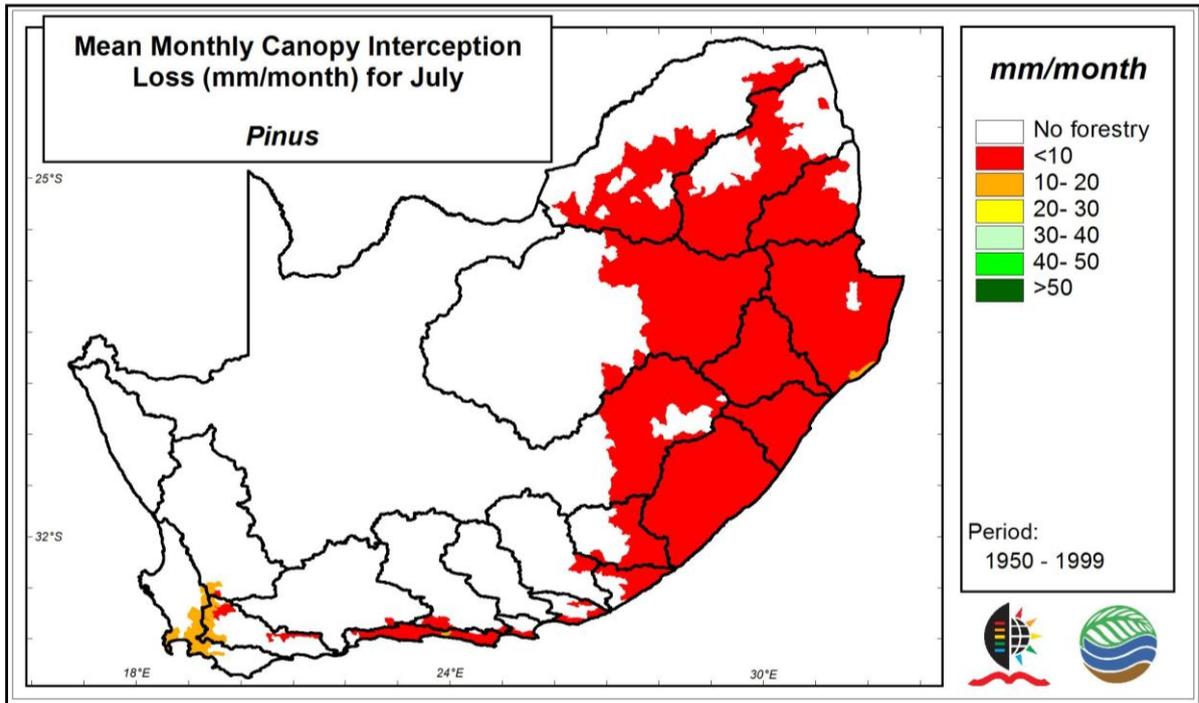
Figure C7   Mean canopy interception loss in July for *Pinus* in South Africa.
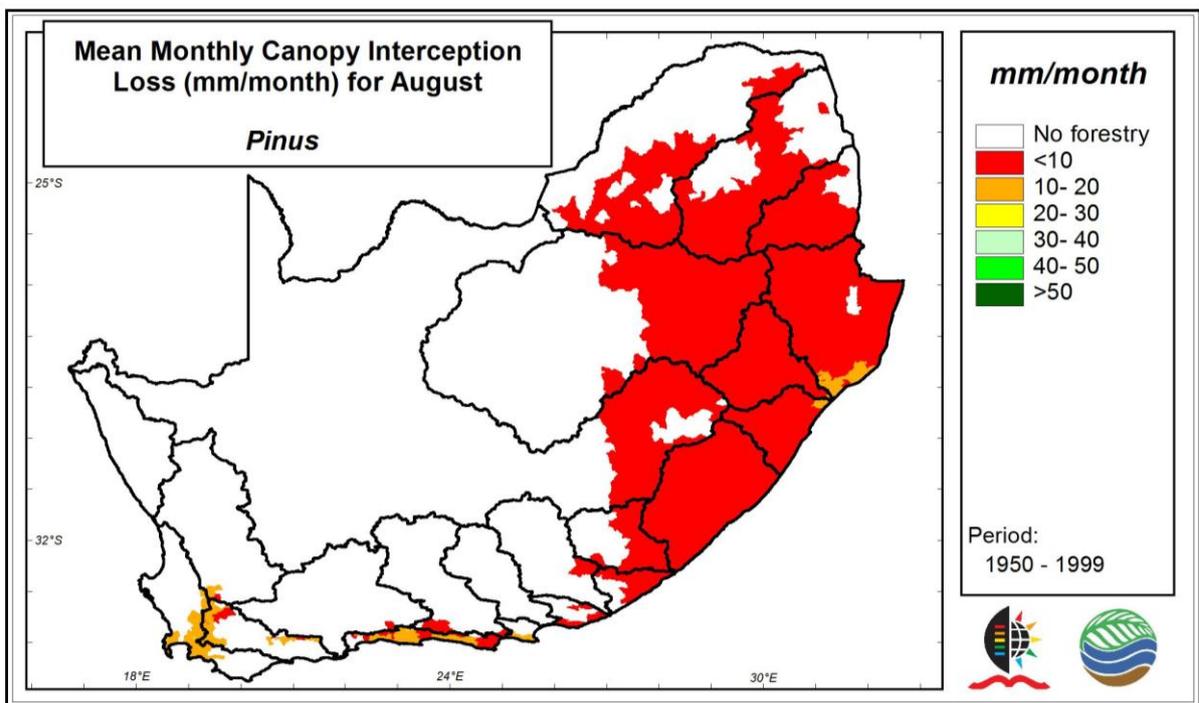
Figure C8   Mean canopy interception loss in August for *Pinus* in South Africa.
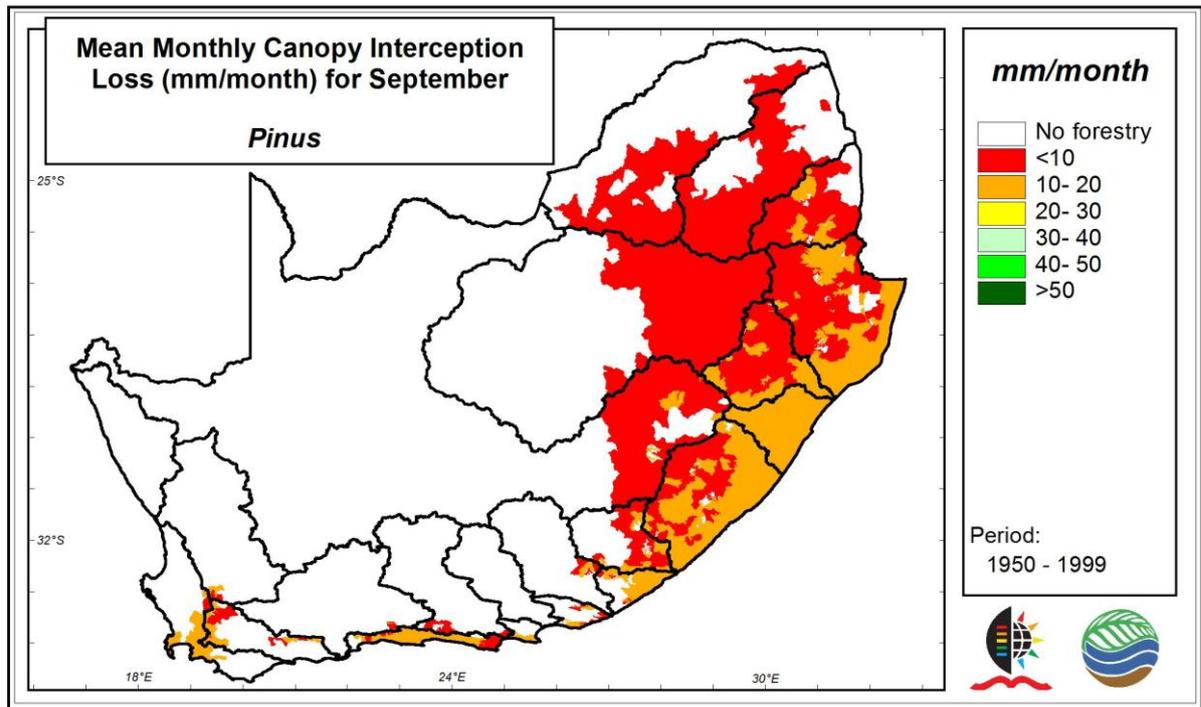
Figure C9   Mean canopy interception loss in September for *Pinus* in South Africa.
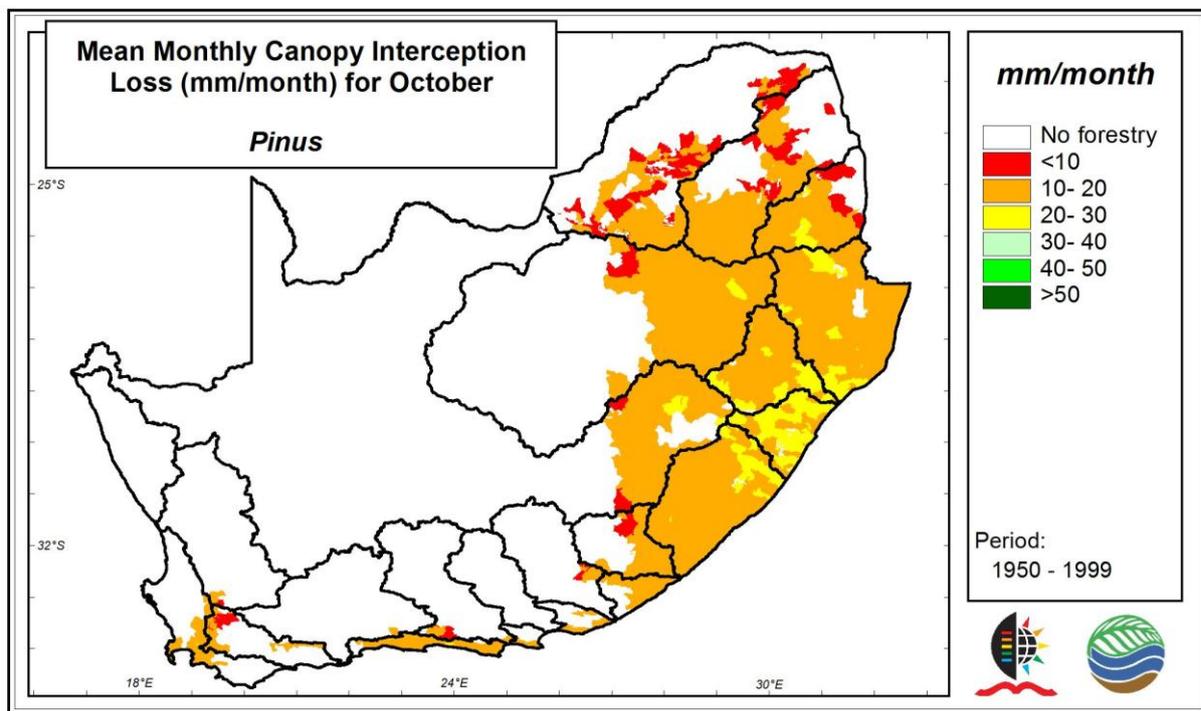
Figure C10   Mean canopy interception loss in October for *Pinus* in South Africa.
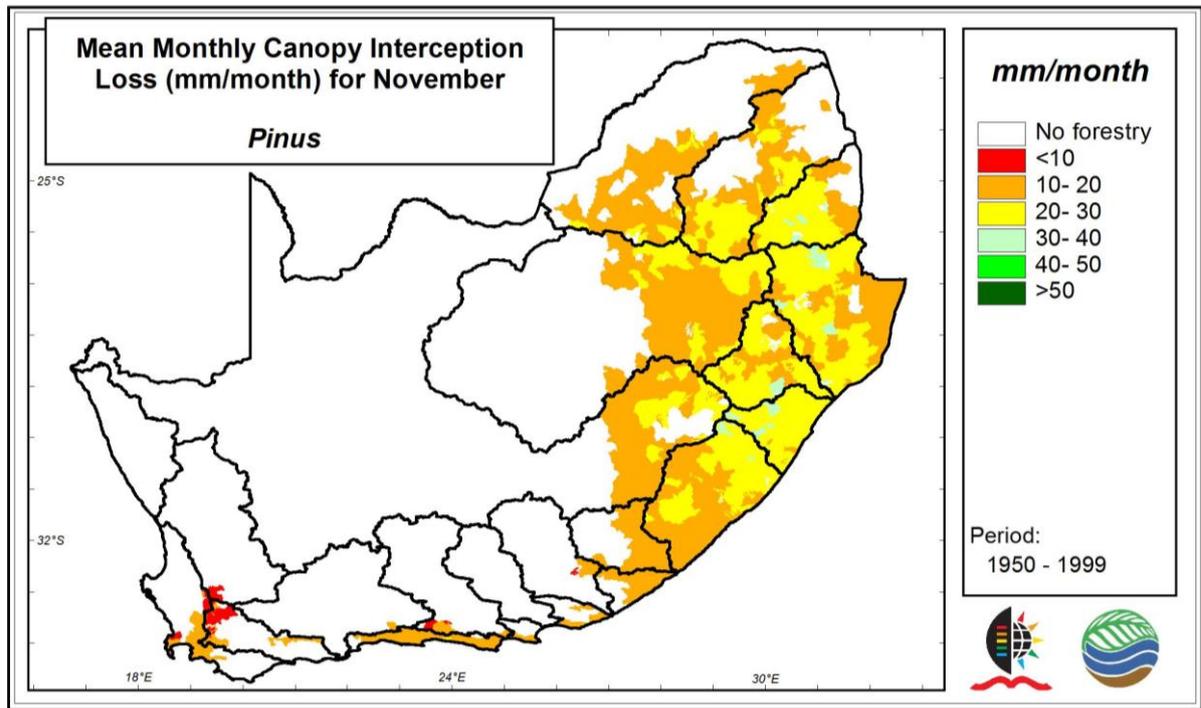
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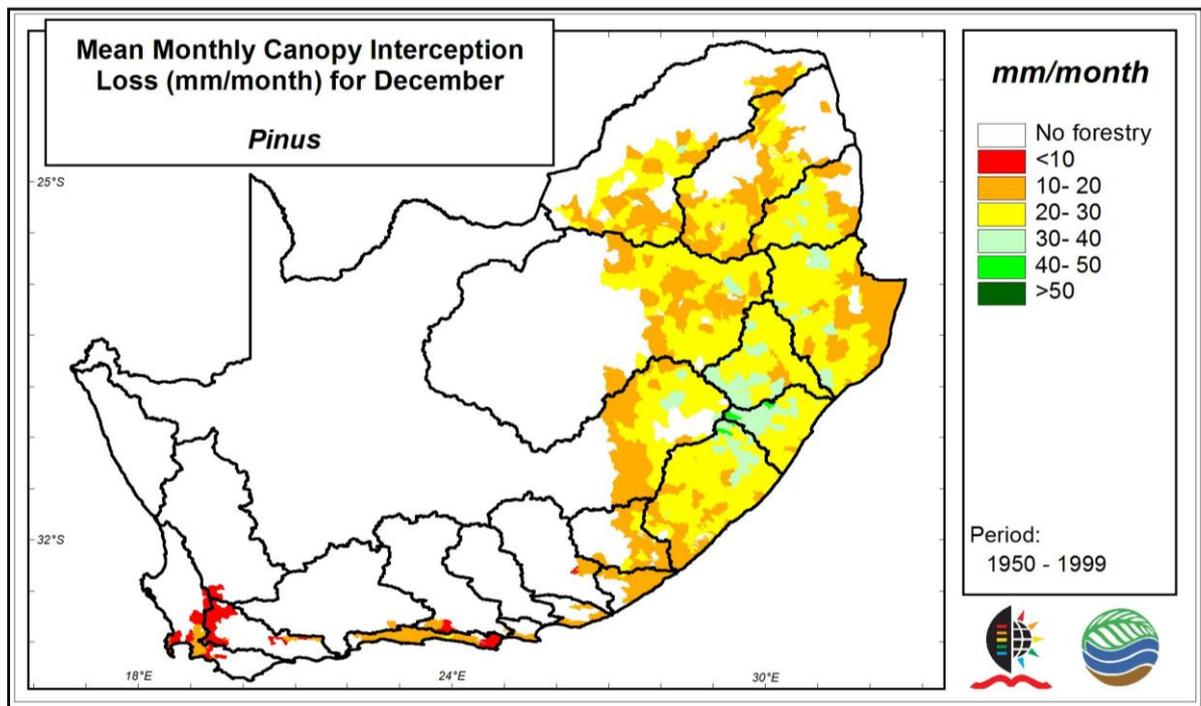
Figure C12   Mean canopy interception loss in December for *Pinus* in South Africa.

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APPENDIX D
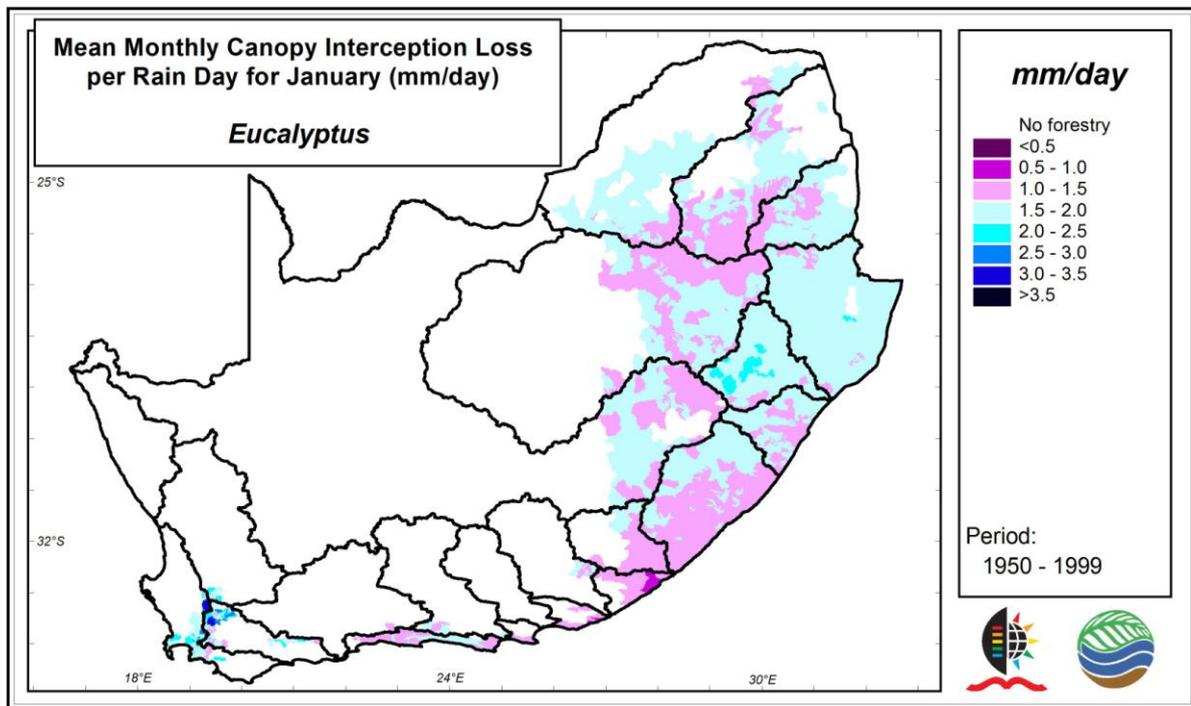
Figure D1   Mean canopy interception loss per rainday in January for *Eucalyptus* in South Africa.
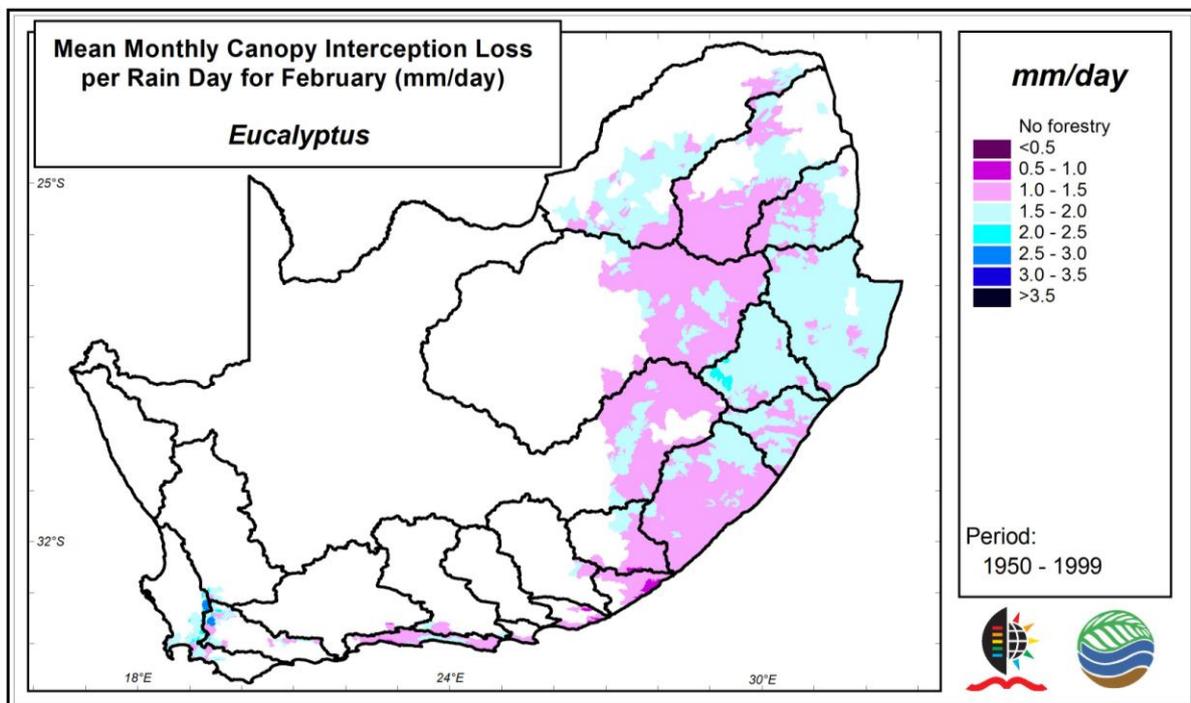
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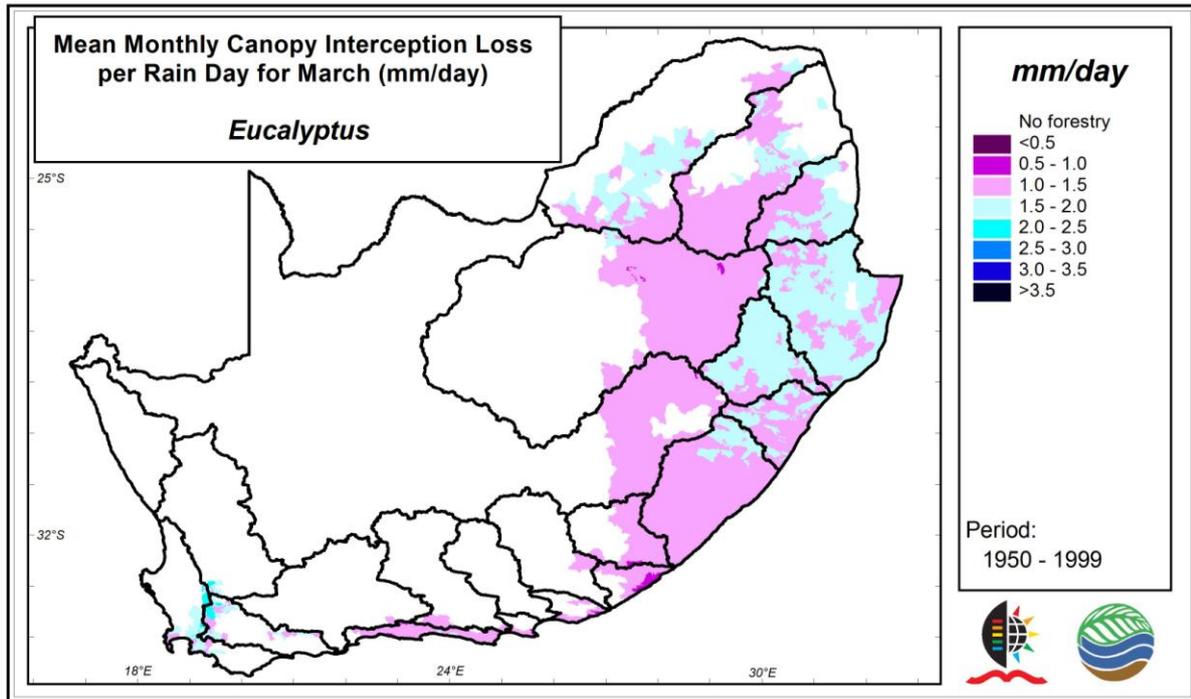
Figure D3   Mean canopy interception loss per rainday in March for *Eucalyptus* in South Africa.
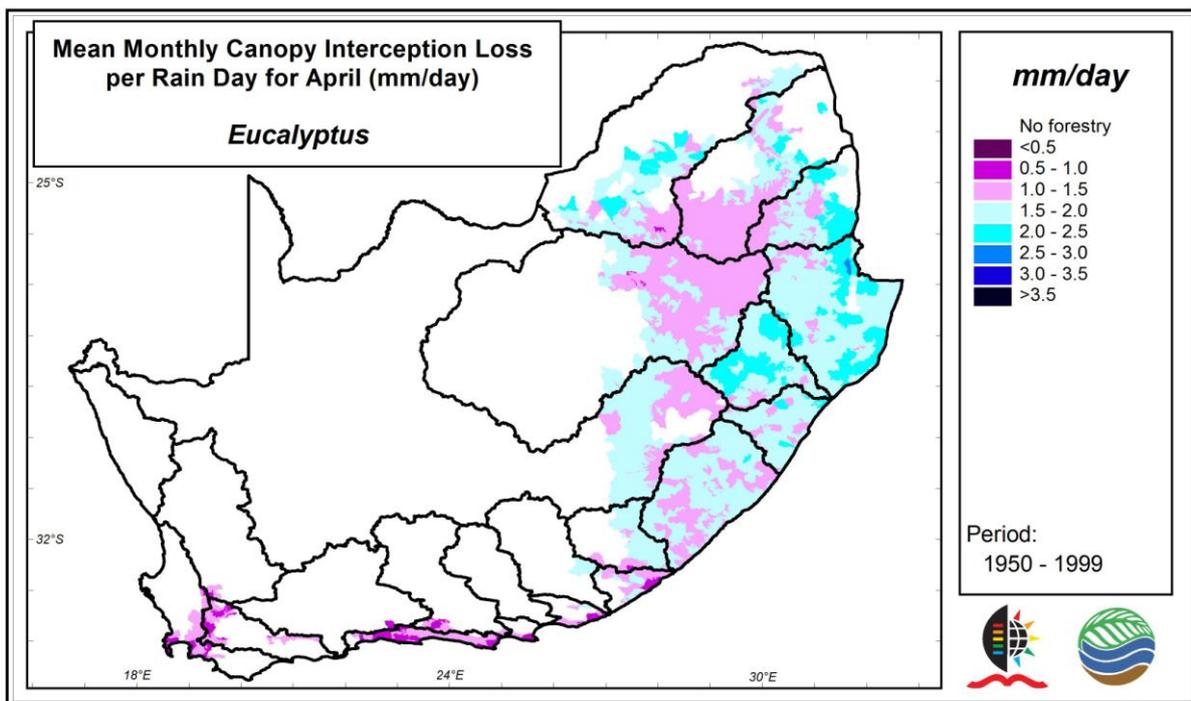
Figure D4   Mean canopy interception loss per rainday in April for *Eucalyptus* in South Africa.
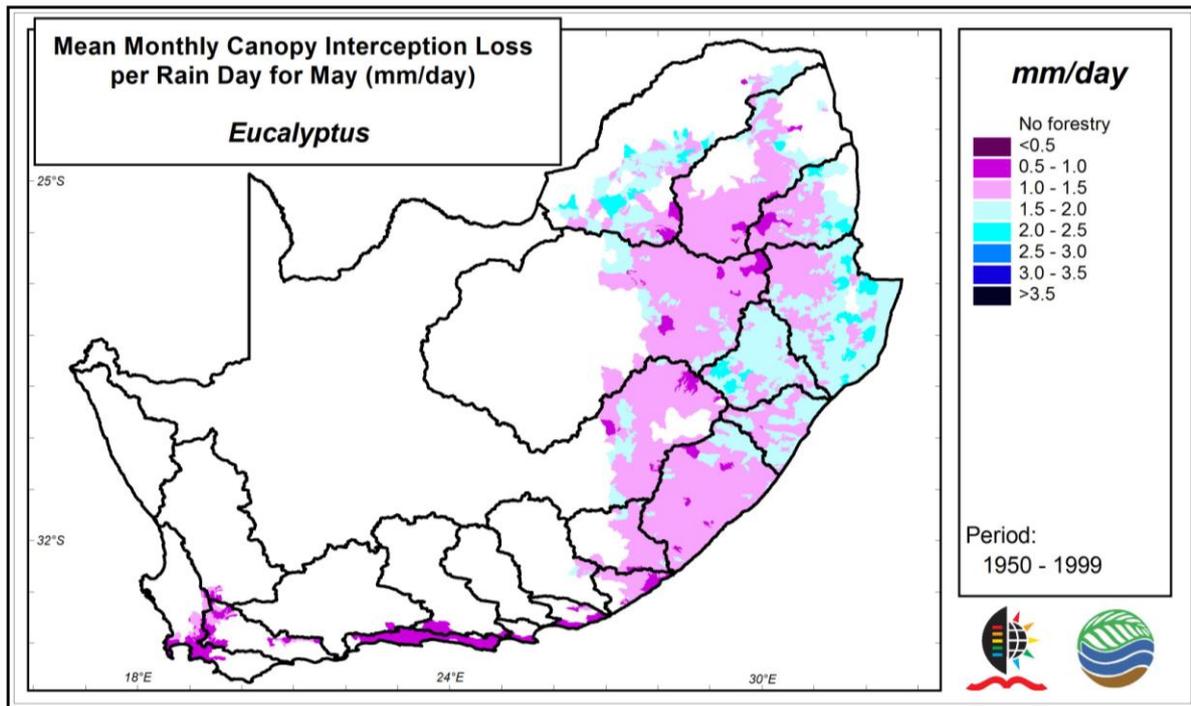
Figure D5   Mean canopy interception loss per rainday in May for *Eucalyptus* in South Africa.
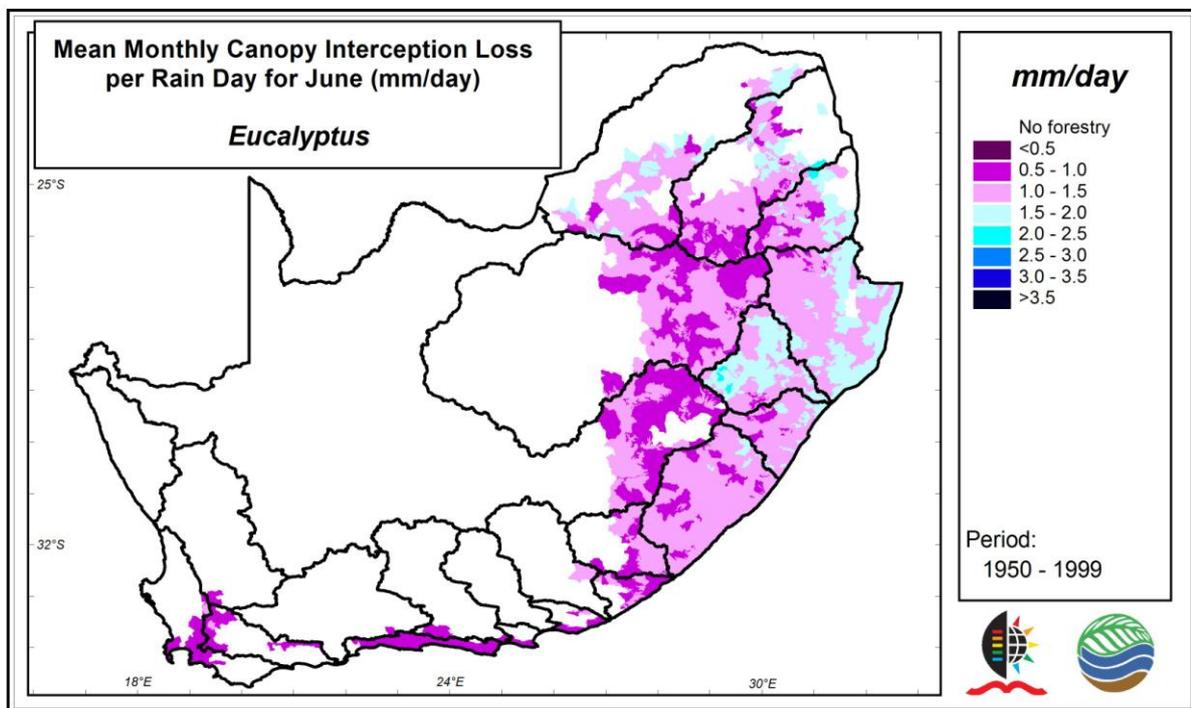
Figure D6   Mean canopy interception loss per rainday in June for *Eucalyptus* in South Africa.
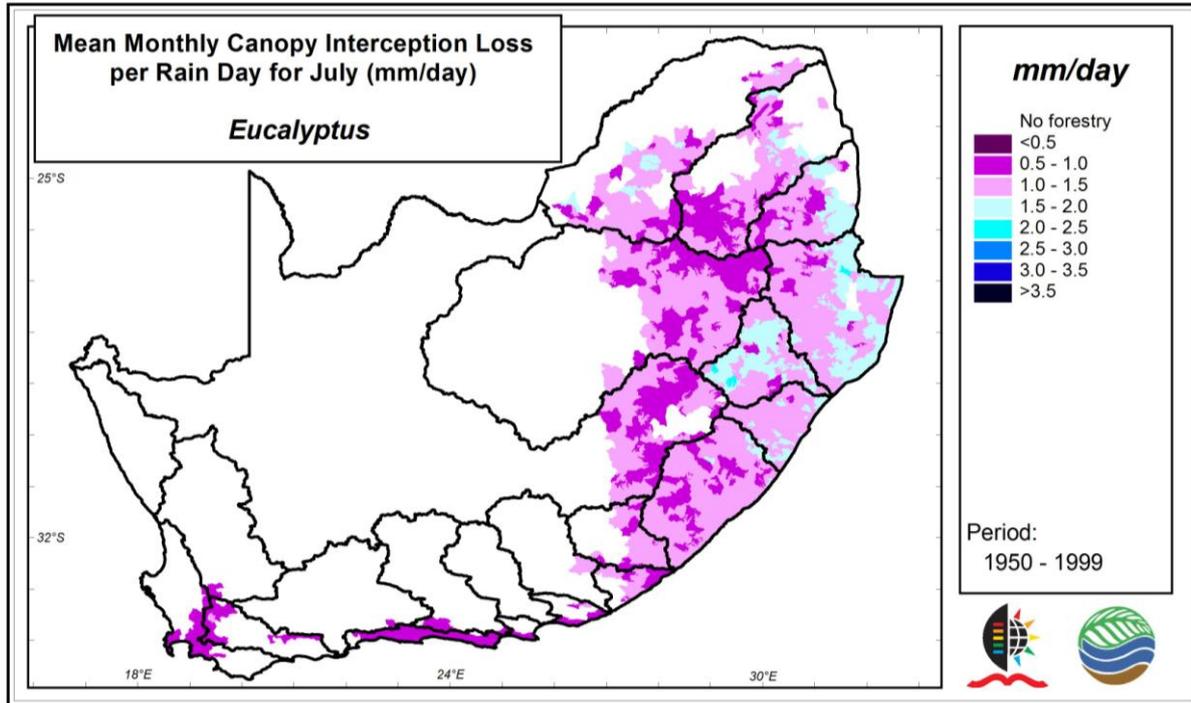
Figure D7   Mean canopy interception loss per rainday in July for *Eucalyptus* in South
             Africa.
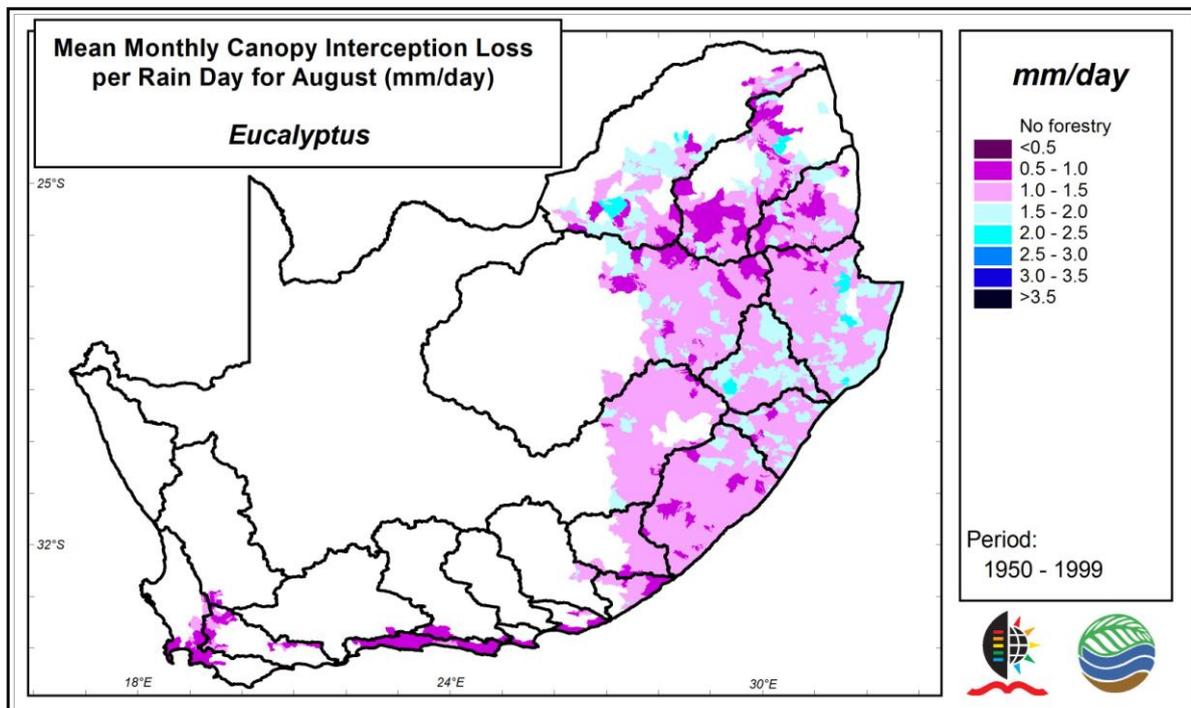
Figure D8   Mean canopy interception loss per rainday in August for *Eucalyptus* in South
             Africa.
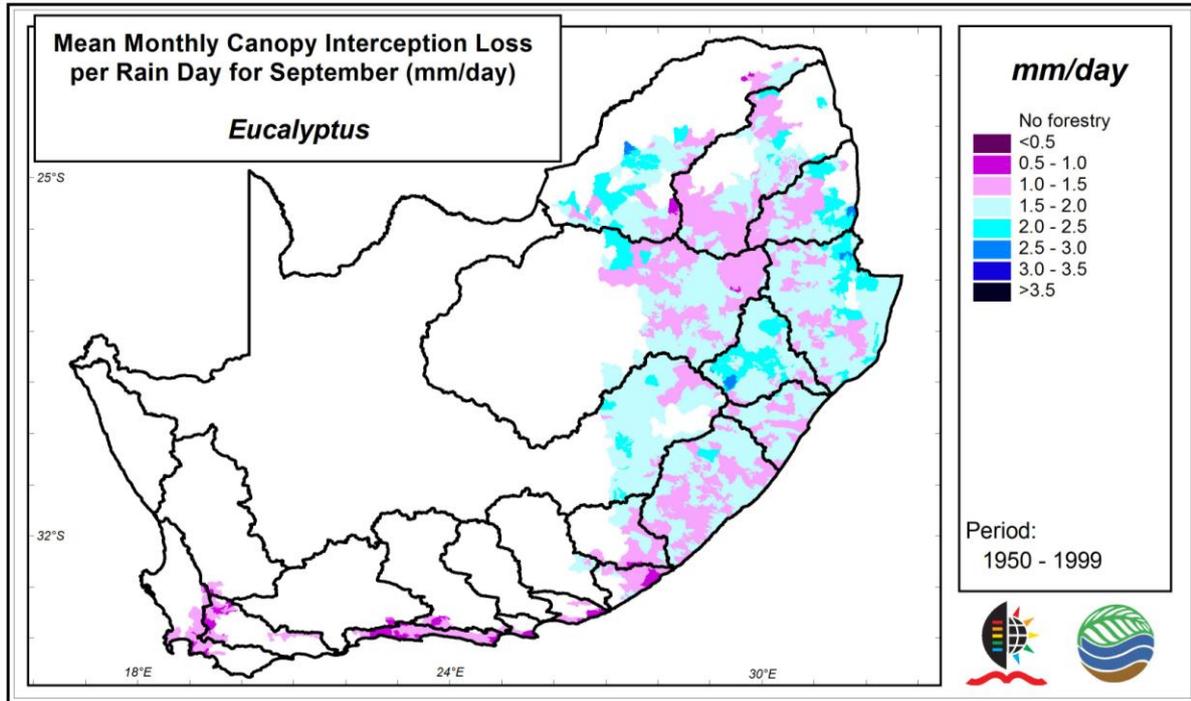
Figure D9   Mean canopy interception loss per rainday in September for *Eucalyptus* in South Africa.
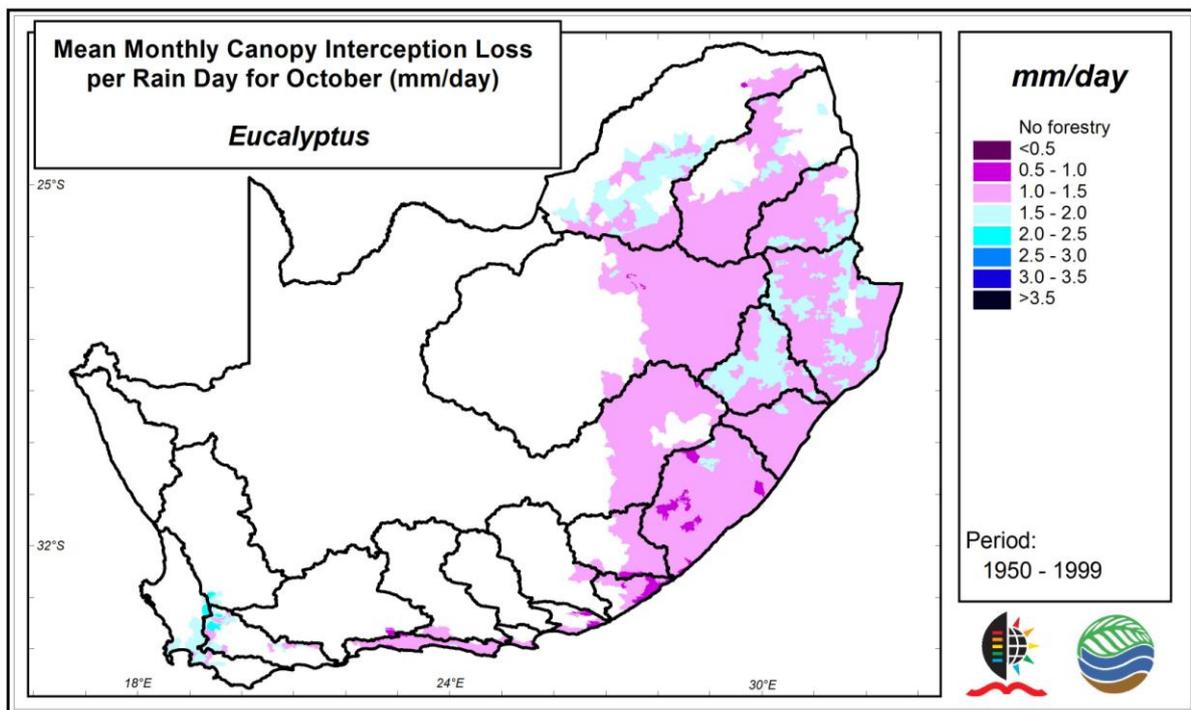
Figure D10   Mean canopy interception loss per rainday in October for *Eucalyptus* in South Africa.
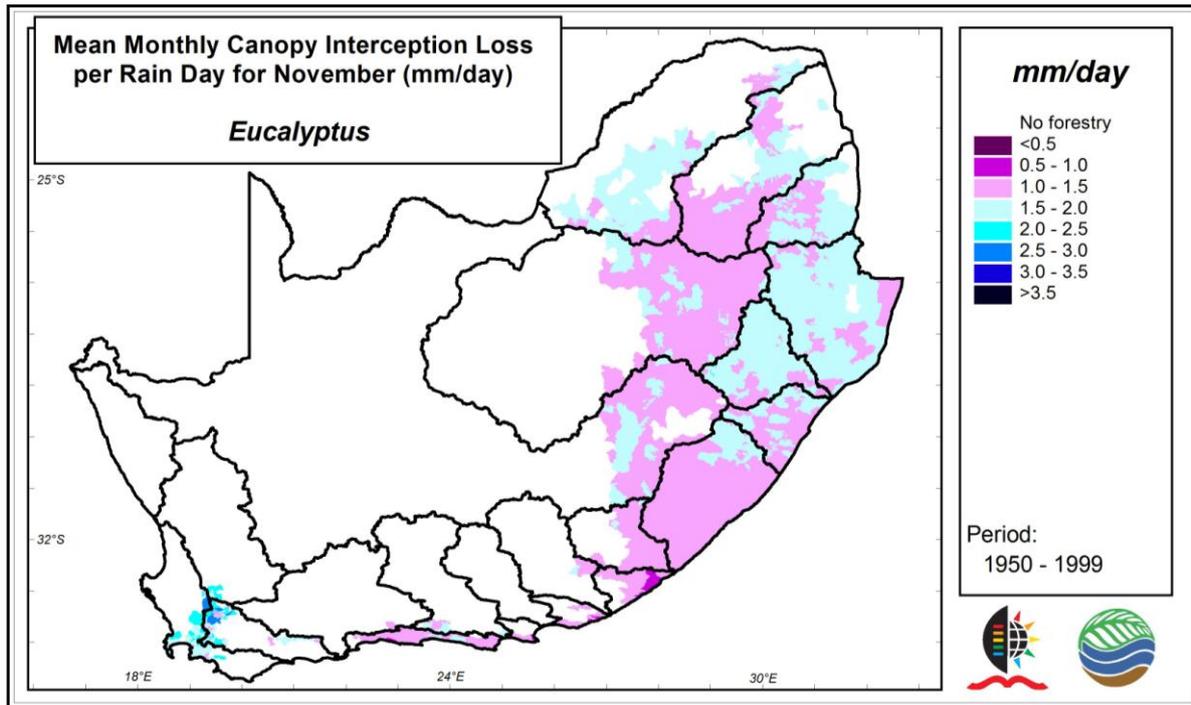
Figure D11   Mean canopy interception loss per rainday in November for *Eucalyptus* in
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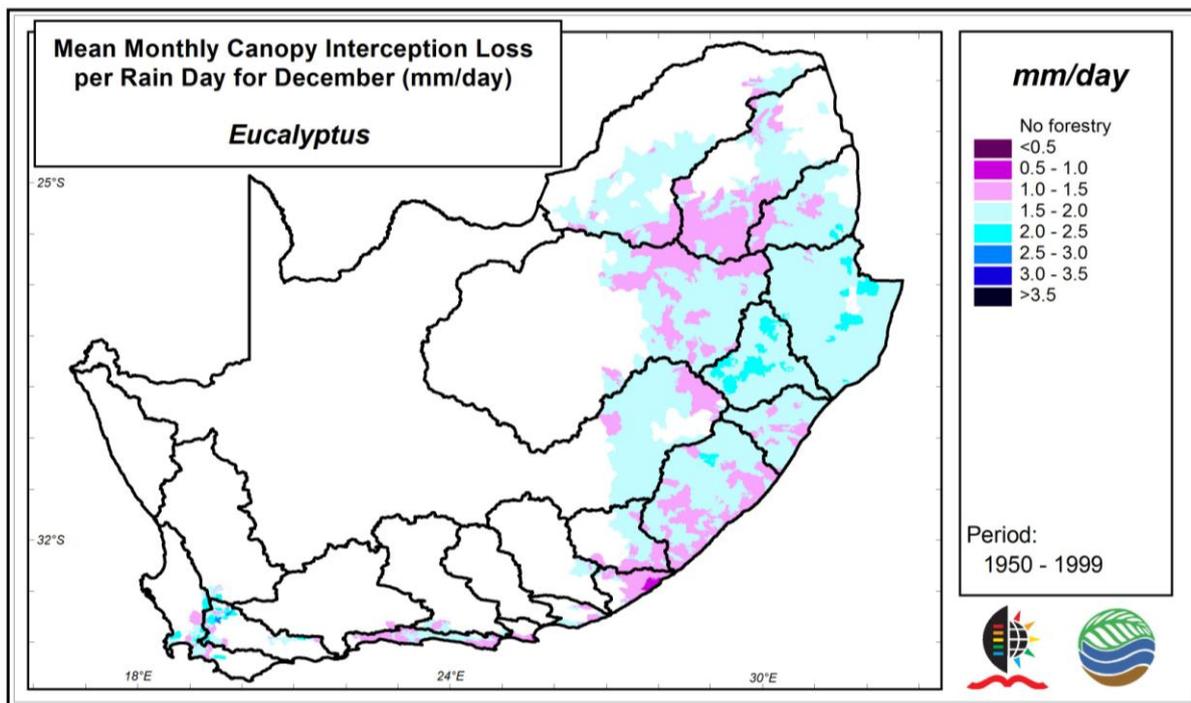
Figure D12   Mean canopy interception loss per rainday in December for *Eucalyptus* in
                 South Africa.

APPENDIX E
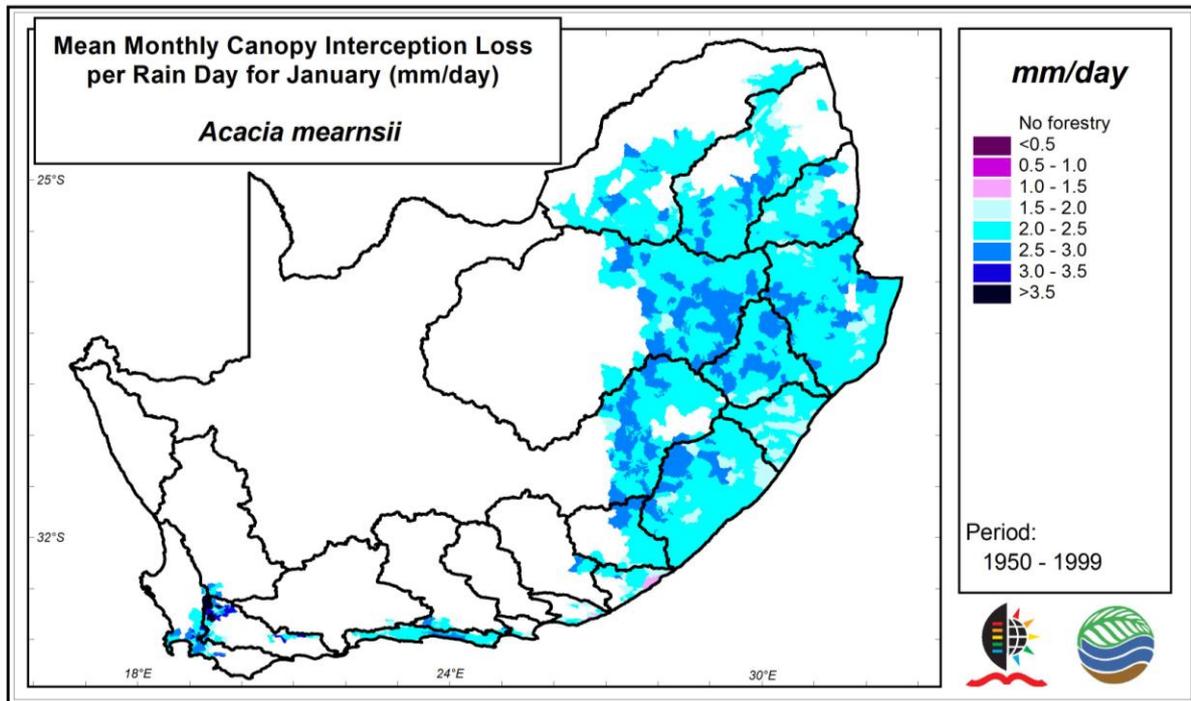
Figure E1   Mean canopy interception loss per rainday in January for *Acacia mearnsii* in South Africa.
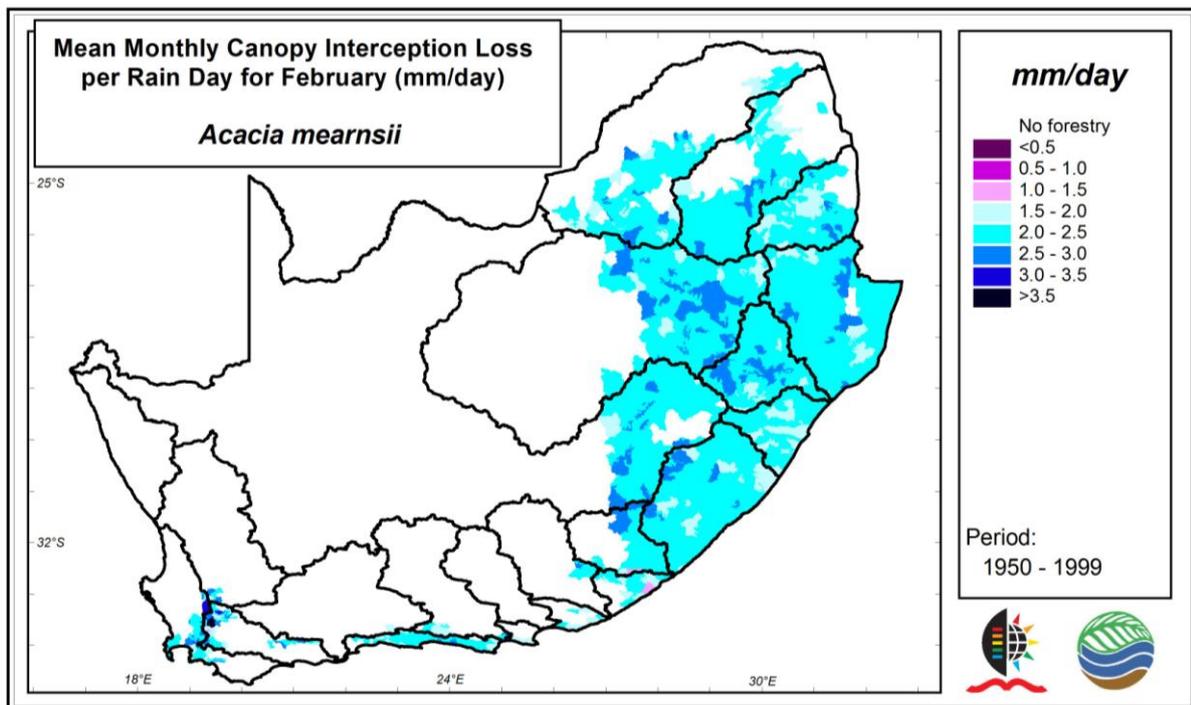
Figure E2   Mean canopy interception loss per rainday in February for *Acacia mearnsii* in South Africa.
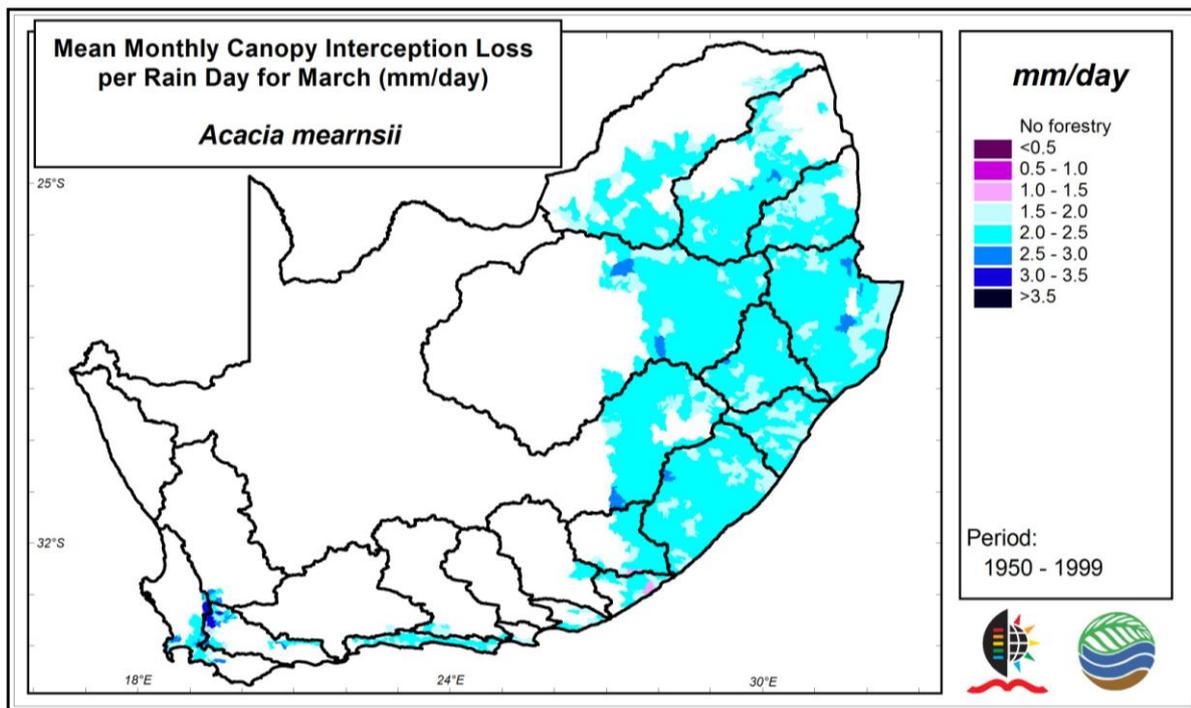
Figure E3   Mean canopy interception loss per rainday in March for *Acacia mearnsii* in
                  South Africa.
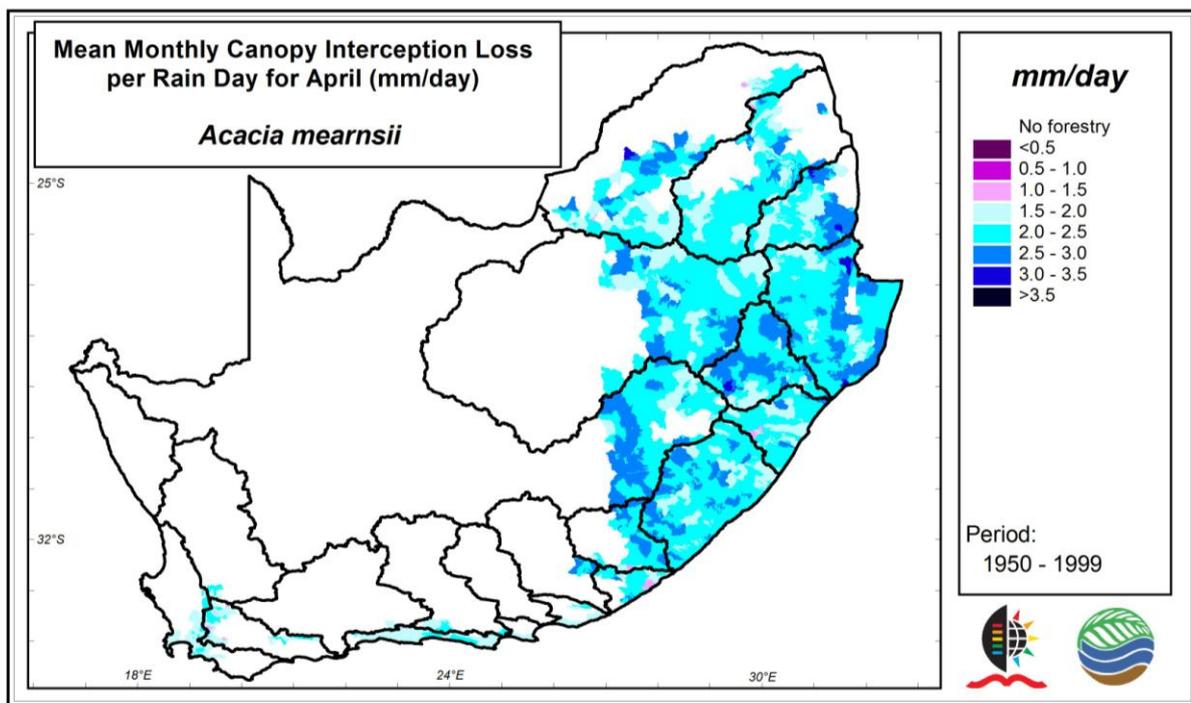
Figure E4   Mean canopy interception loss per rainday in April for *Acacia mearnsii* in
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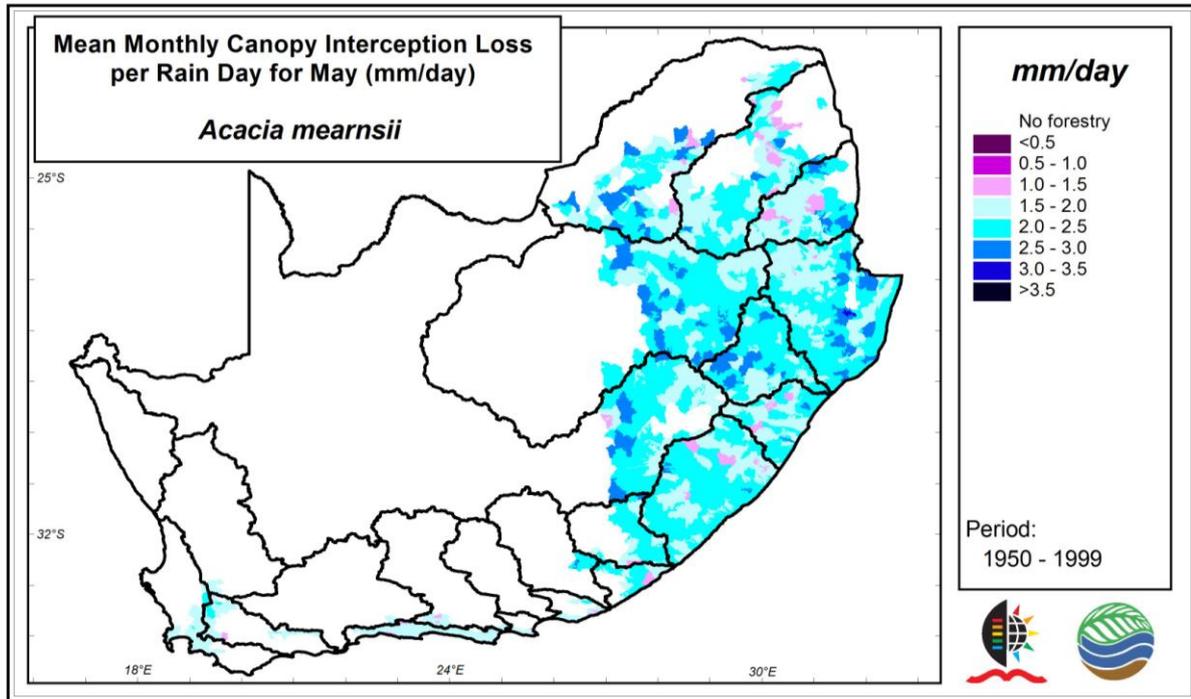
Figure E5   Mean canopy interception loss per rainday in May for *Acacia mearnsii* in
             South Africa.
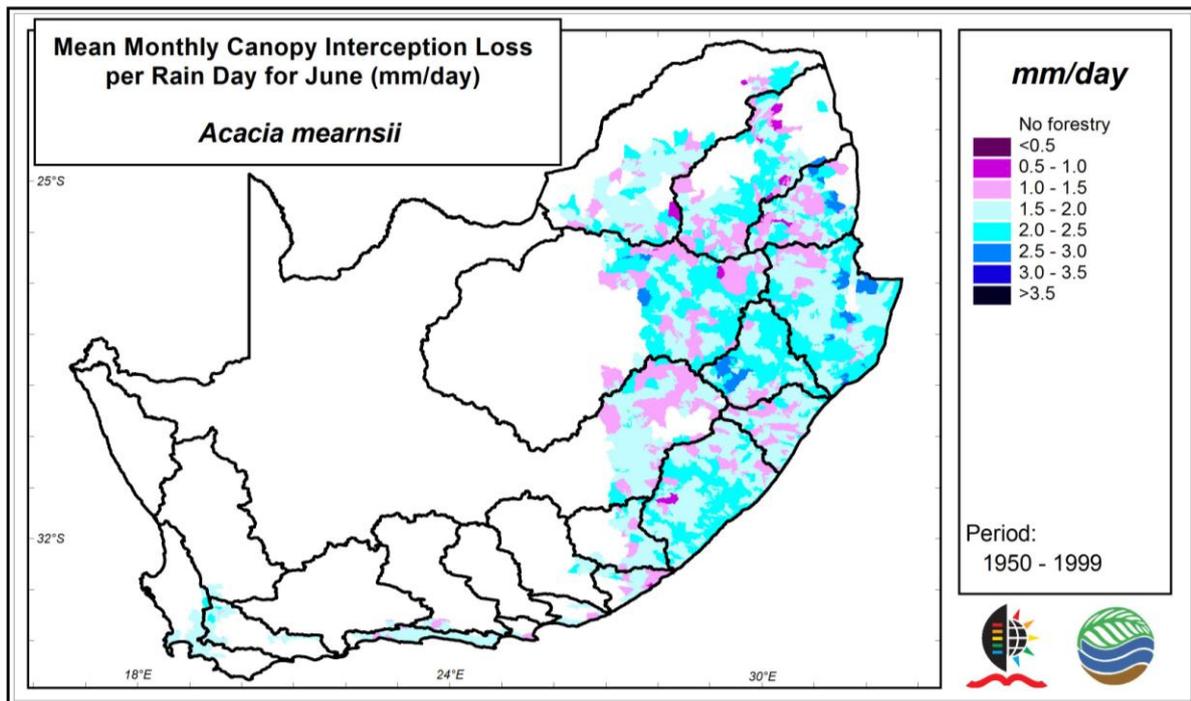
Figure E6   Mean canopy interception loss per rainday in June for *Acacia mearnsii* in
             South Africa.
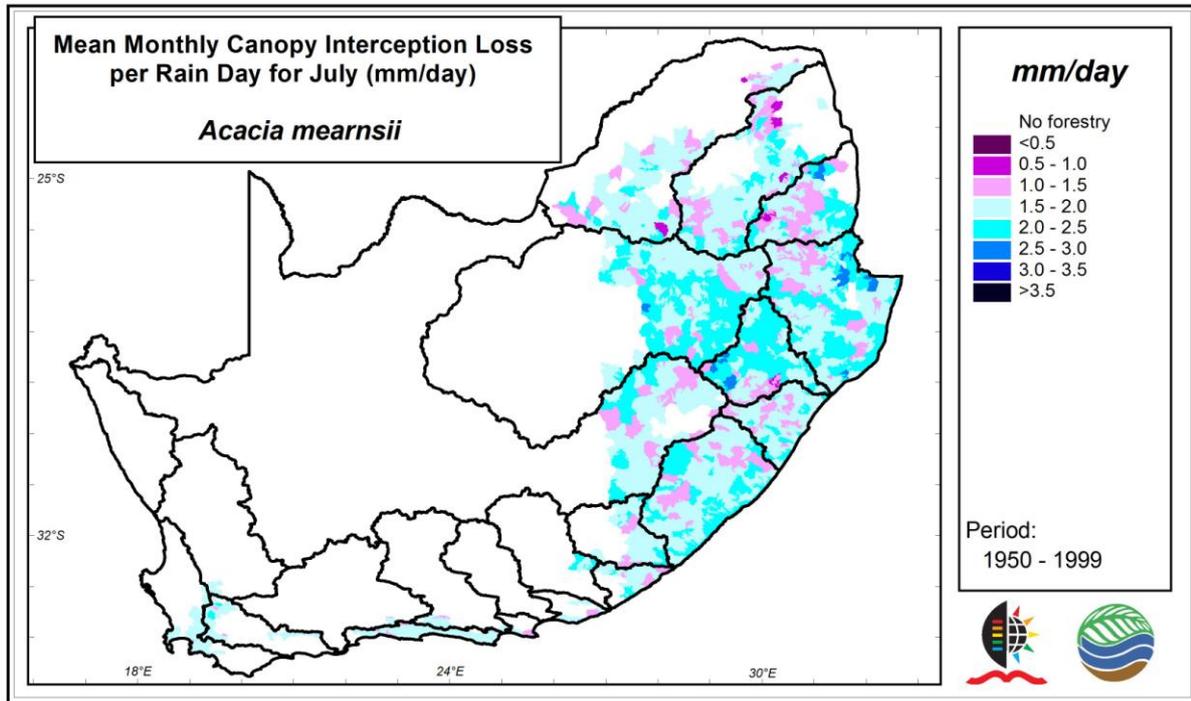
Figure E7   Mean canopy interception loss per rainday in July for *Acacia mearnsii* in
             South Africa.
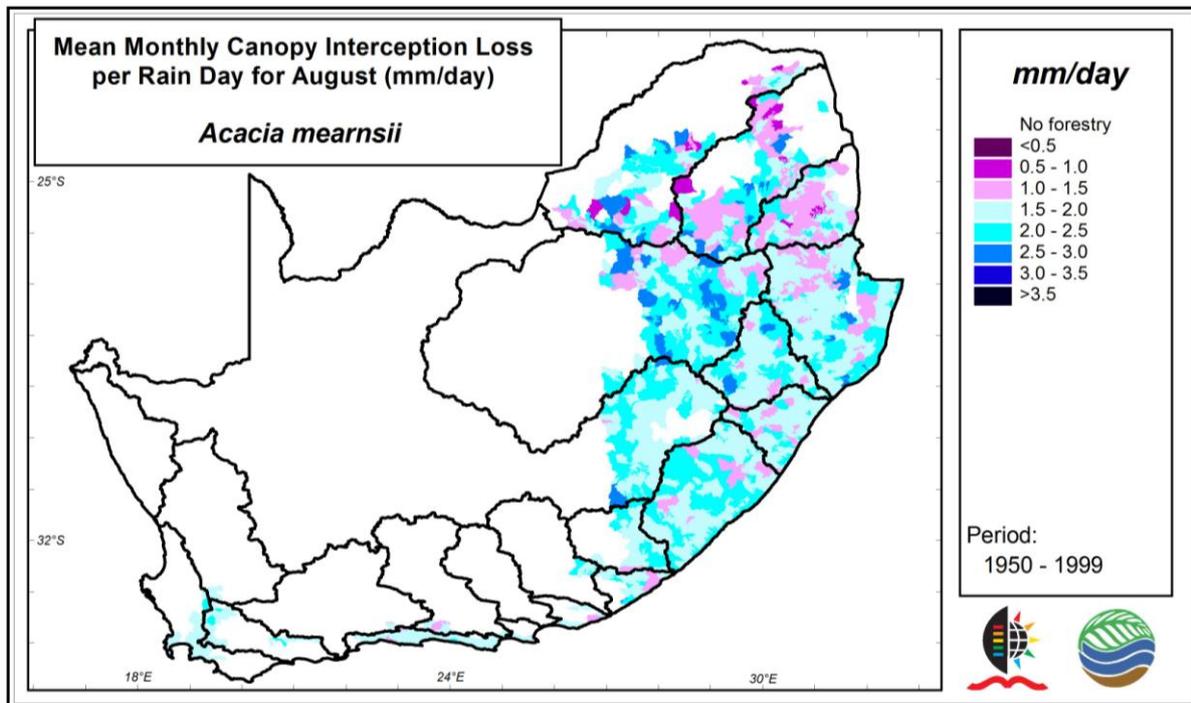
Figure E8   Mean canopy interception loss per rainday in August for *Acacia mearnsii* in
             South Africa.
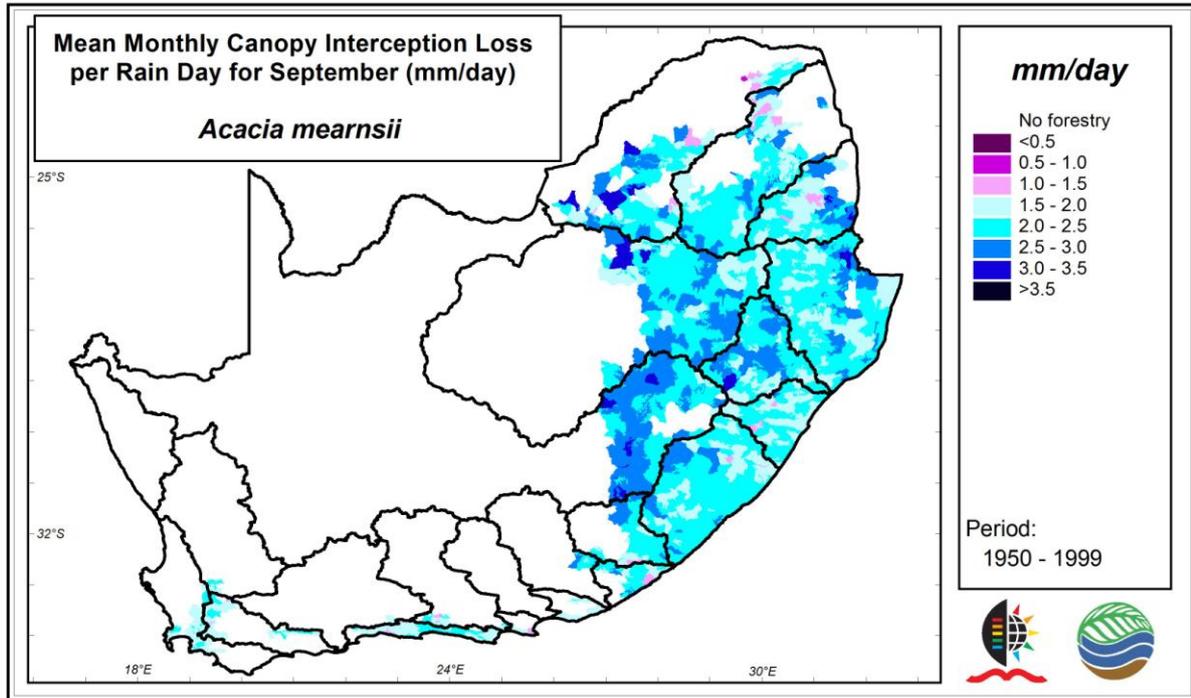
Figure E9   Mean canopy interception loss per rainday in September for *Acacia mearnsii* in South Africa.
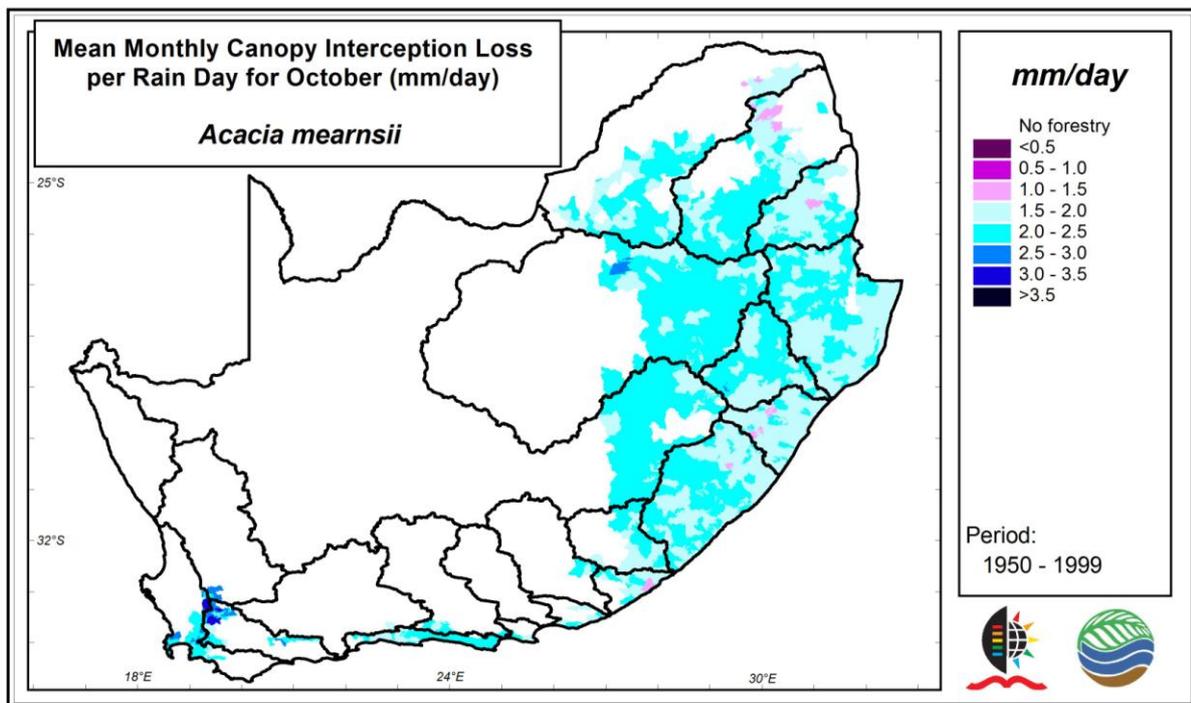
Figure E10   Mean canopy interception loss per rainday in October for *Acacia mearnsii* in South Africa.

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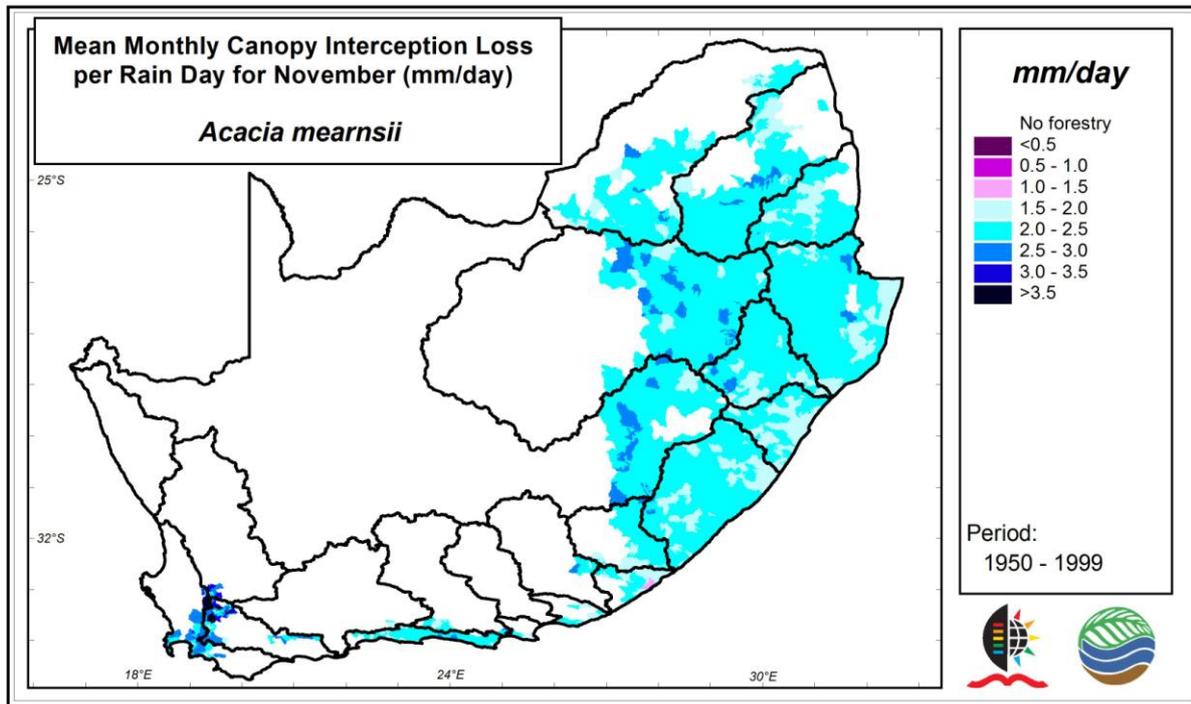
Figure E11   Mean canopy interception loss per rainday in November for *Acacia mearnsii* in South Africa.
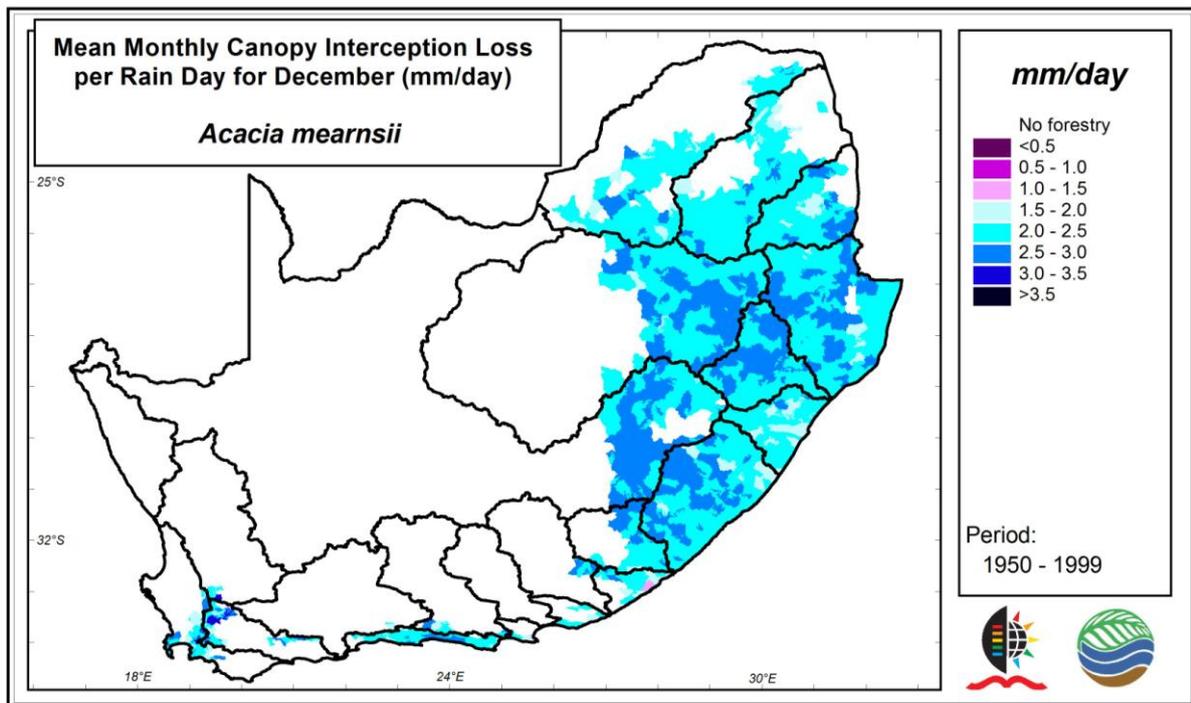
Figure E12   Mean canopy interception loss per rainday in December for *Acacia mearnsii* in South Africa.

APPENDIX F
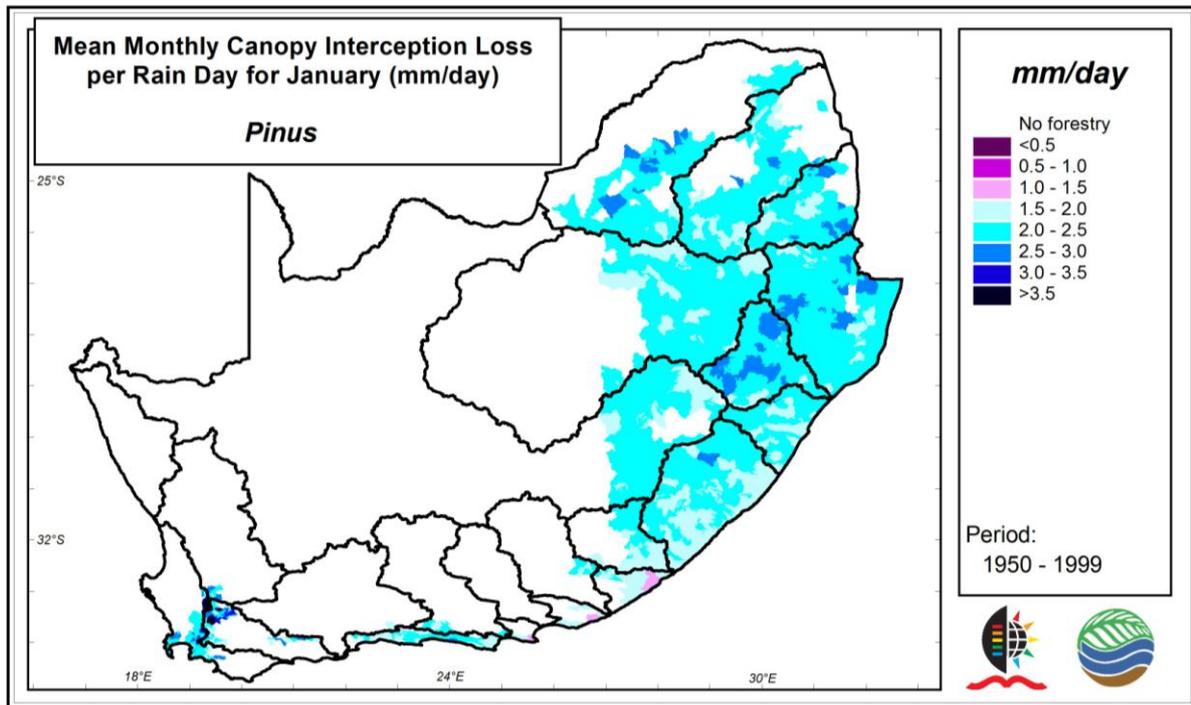
Figure F1   Mean canopy interception loss per rainday in January for *Pinus* in South Africa.
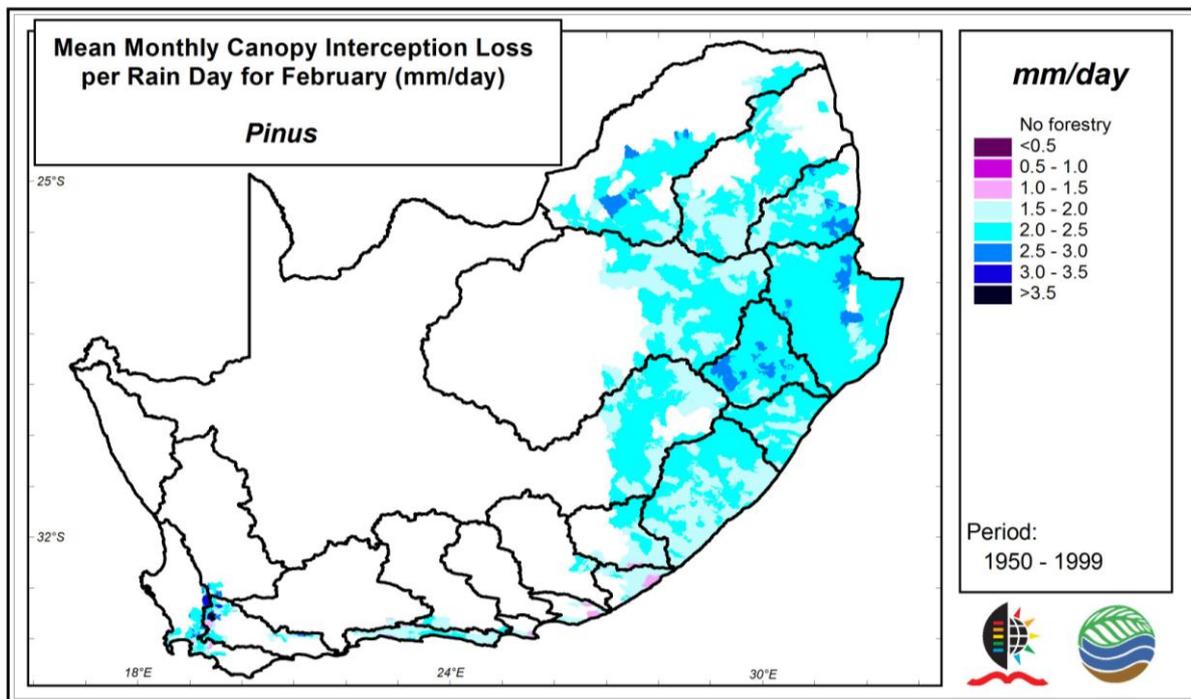
Figure F2   Mean canopy interception loss per rainday in February for *Pinus* in South Africa.
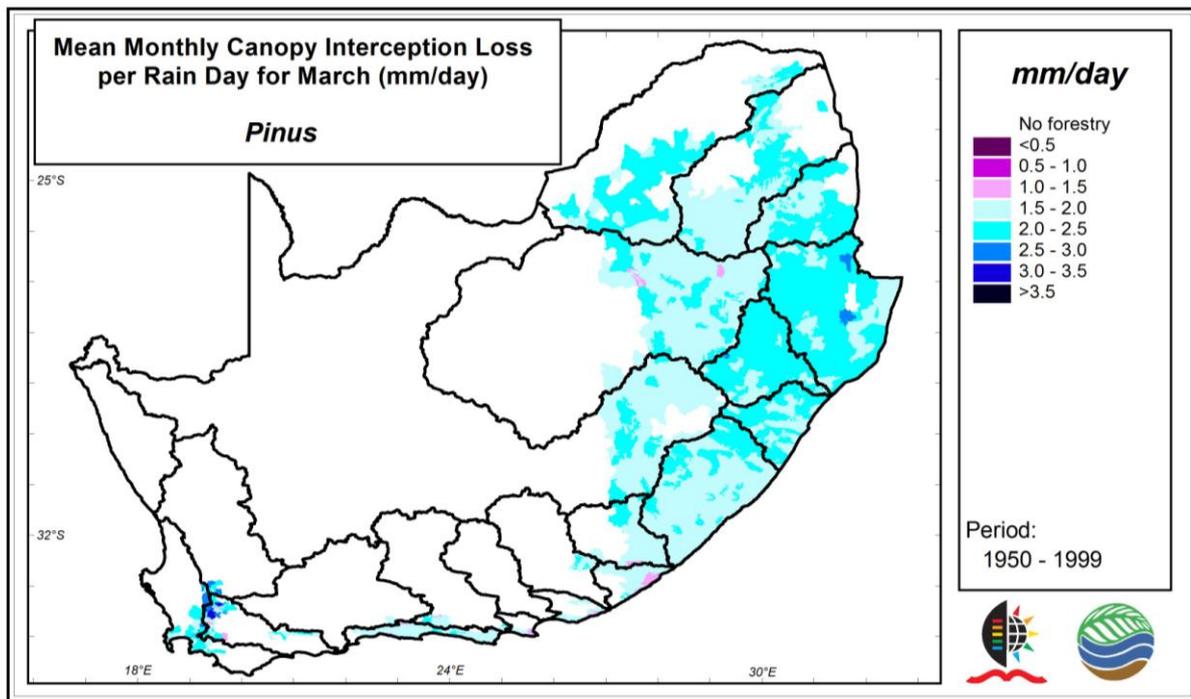
Figure F3   Mean canopy interception loss per rainday in March for *Pinus* in South Africa.
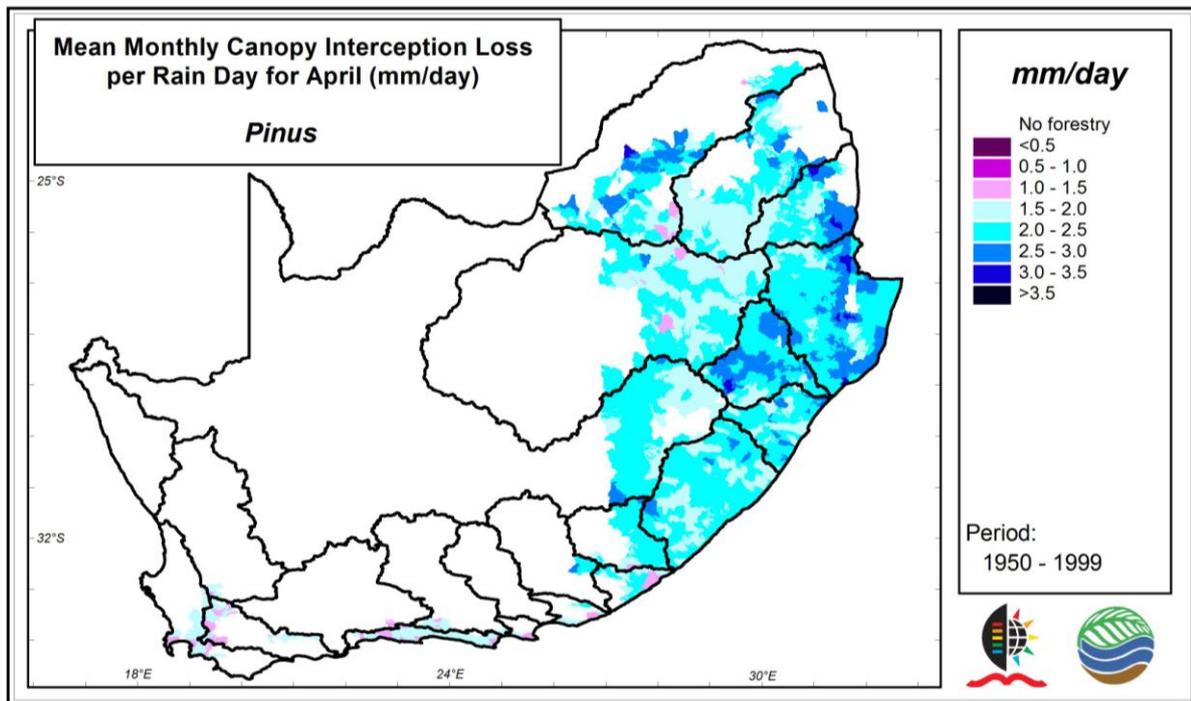
Figure F4   Mean canopy interception loss per rainday in April for *Pinus* in South Africa.
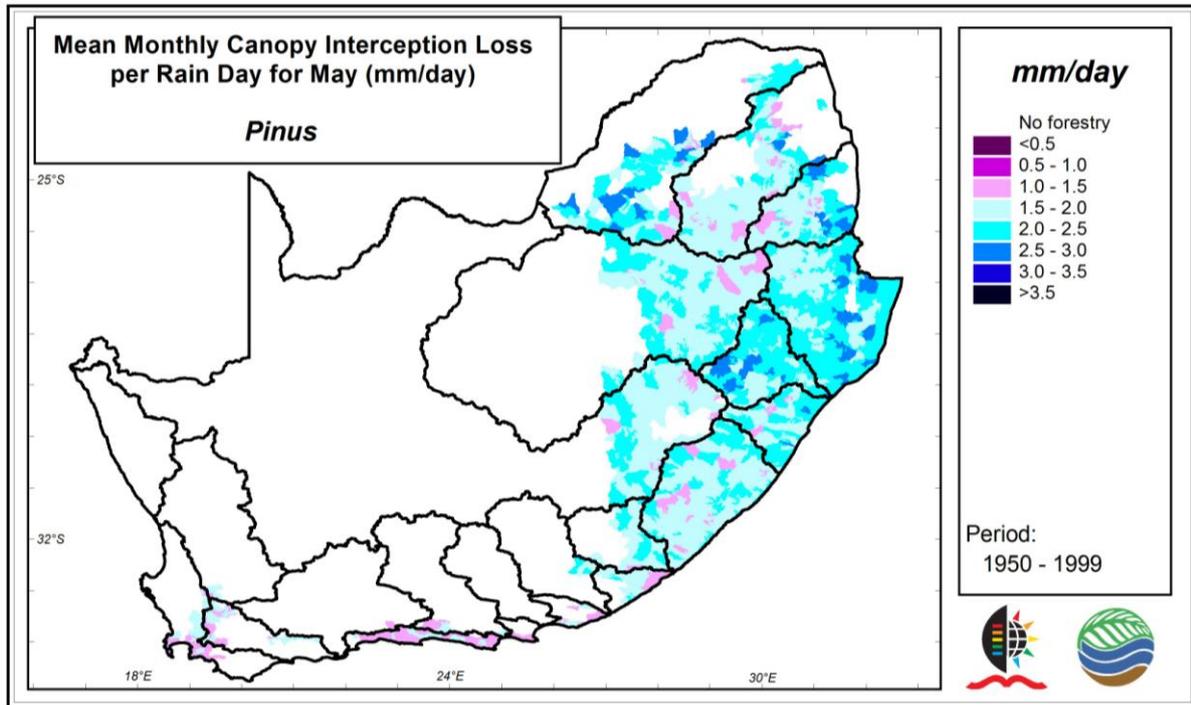
Figure F5   Mean canopy interception loss per rainday in May for *Pinus* in South Africa.
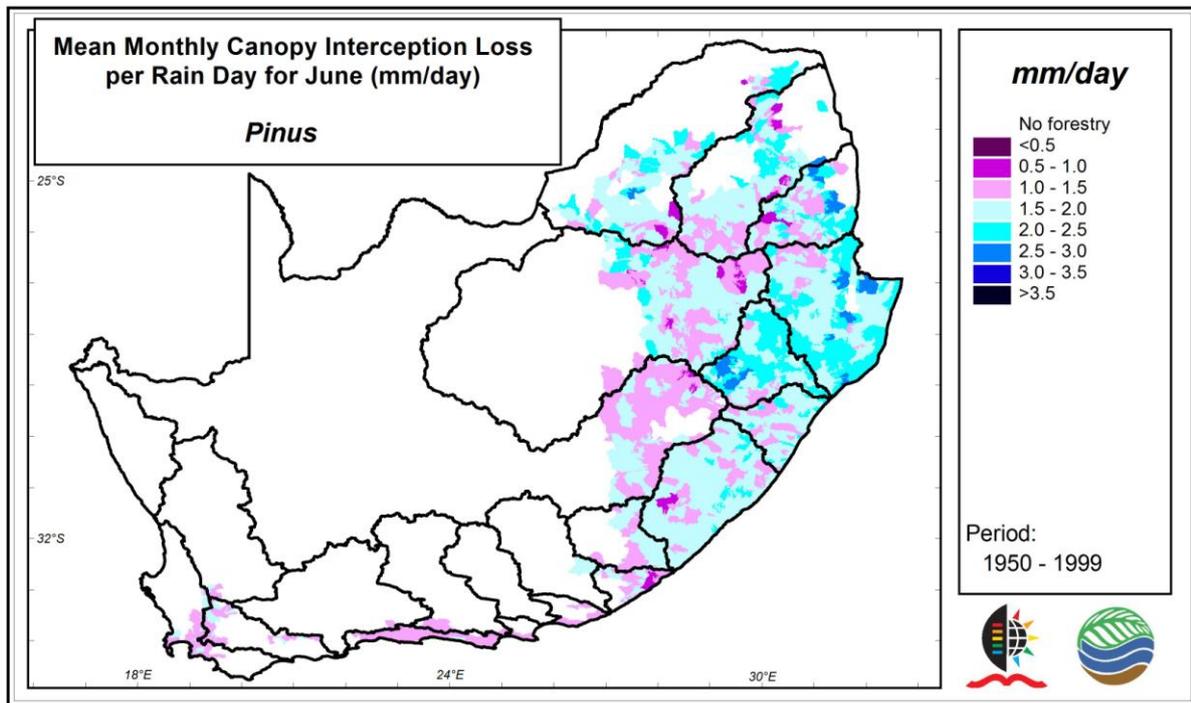
Figure F6   Mean canopy interception loss per rainday in June for *Pinus* in South Africa.
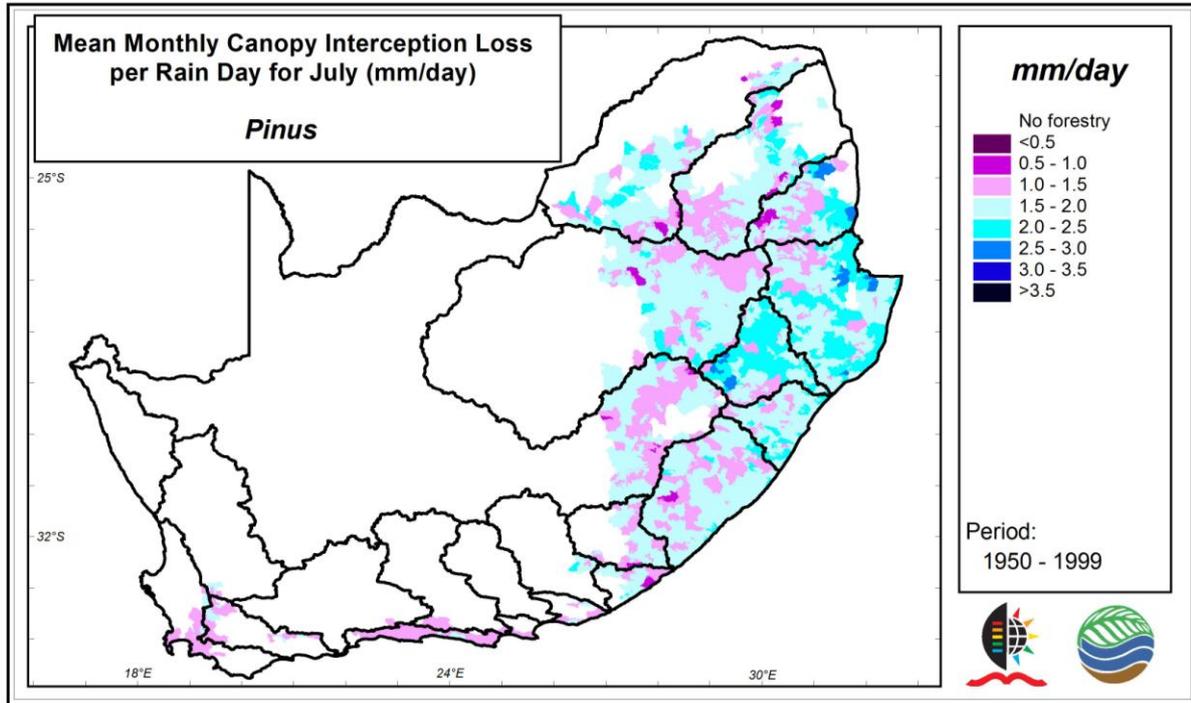
Figure F7   Mean canopy interception loss per rainday in July for *Pinus* in South Africa.
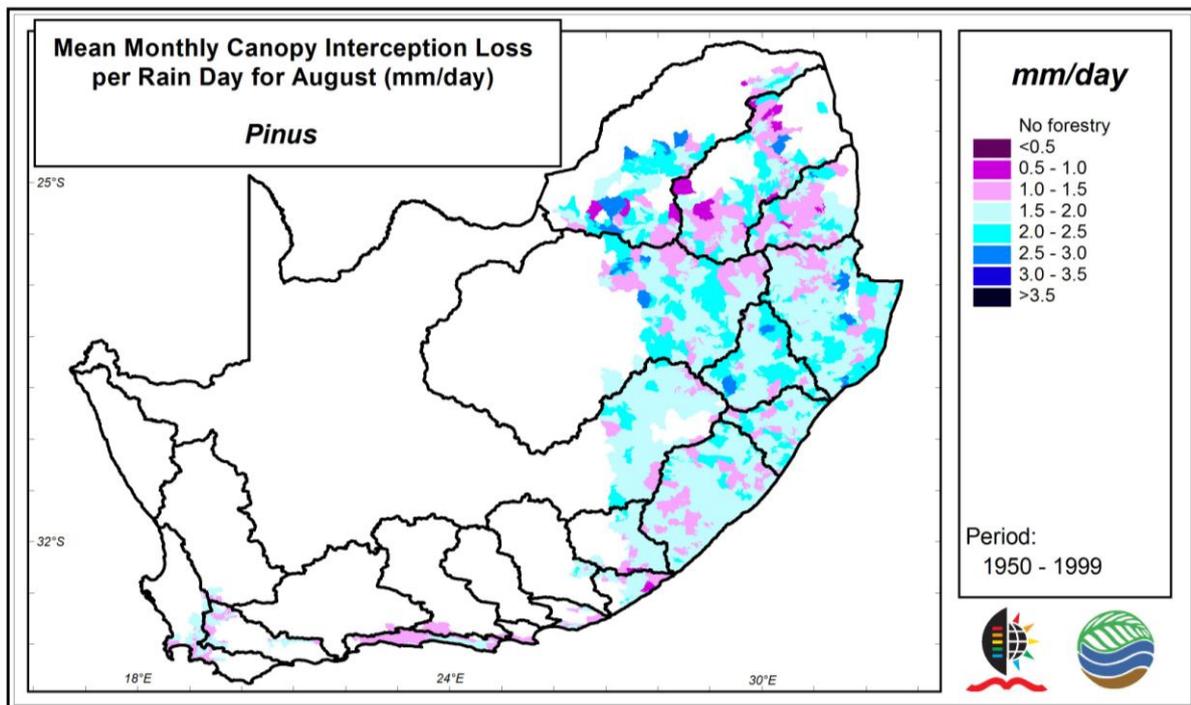
Figure F8   Mean canopy interception loss per rainday in August for *Pinus* in South Africa.
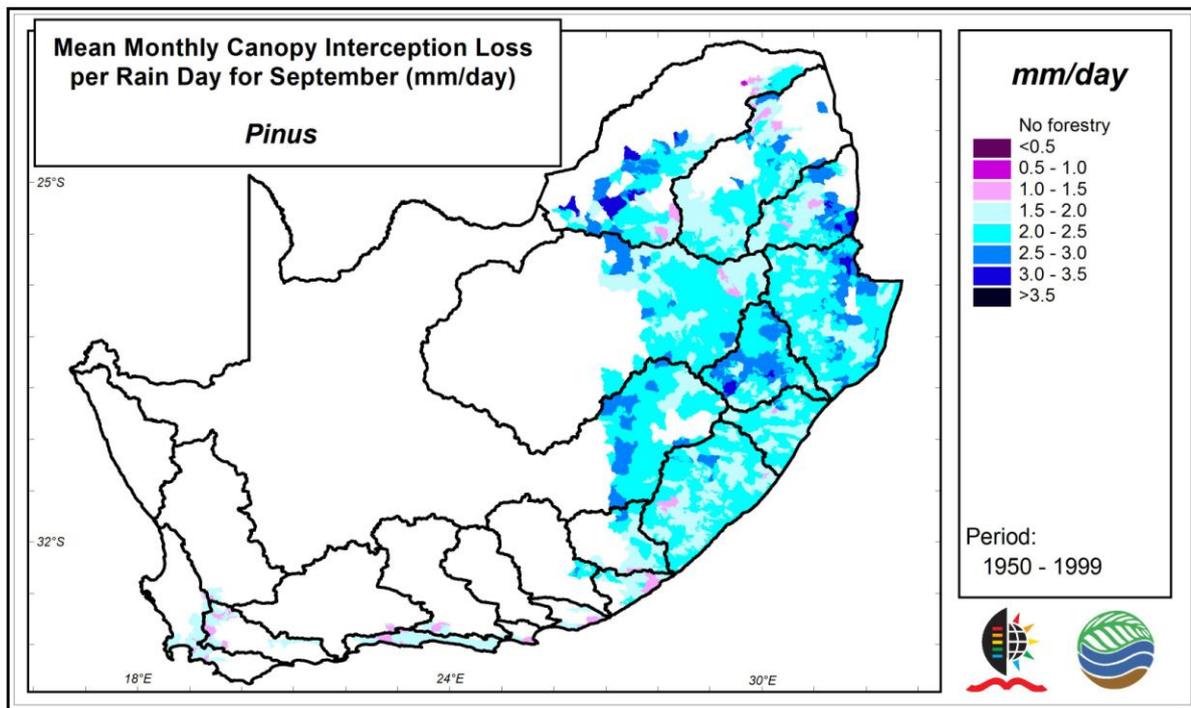
Figure F9   Mean canopy interception loss per rainday in September for *Pinus* in South Africa.
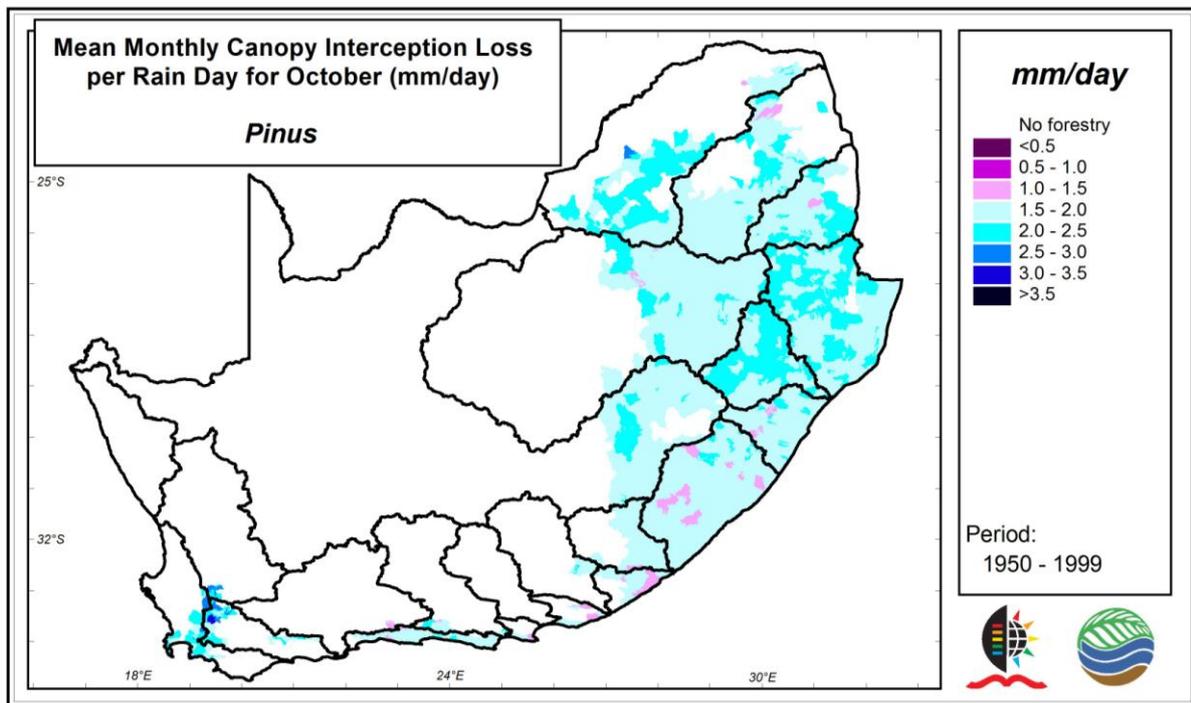
Figure F10   Mean canopy interception loss per rainday in October for *Pinus* in South Africa.
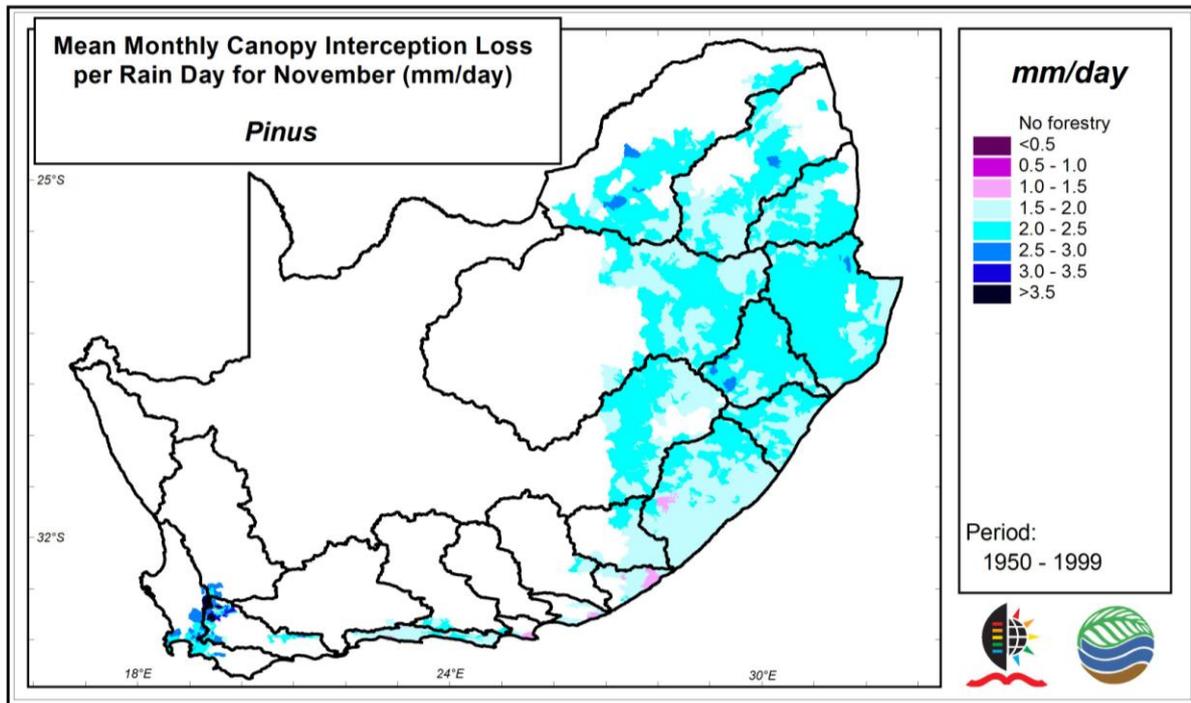
Figure F11　　　Mean canopy interception loss per rainday in November for *Pinus* in South Africa.
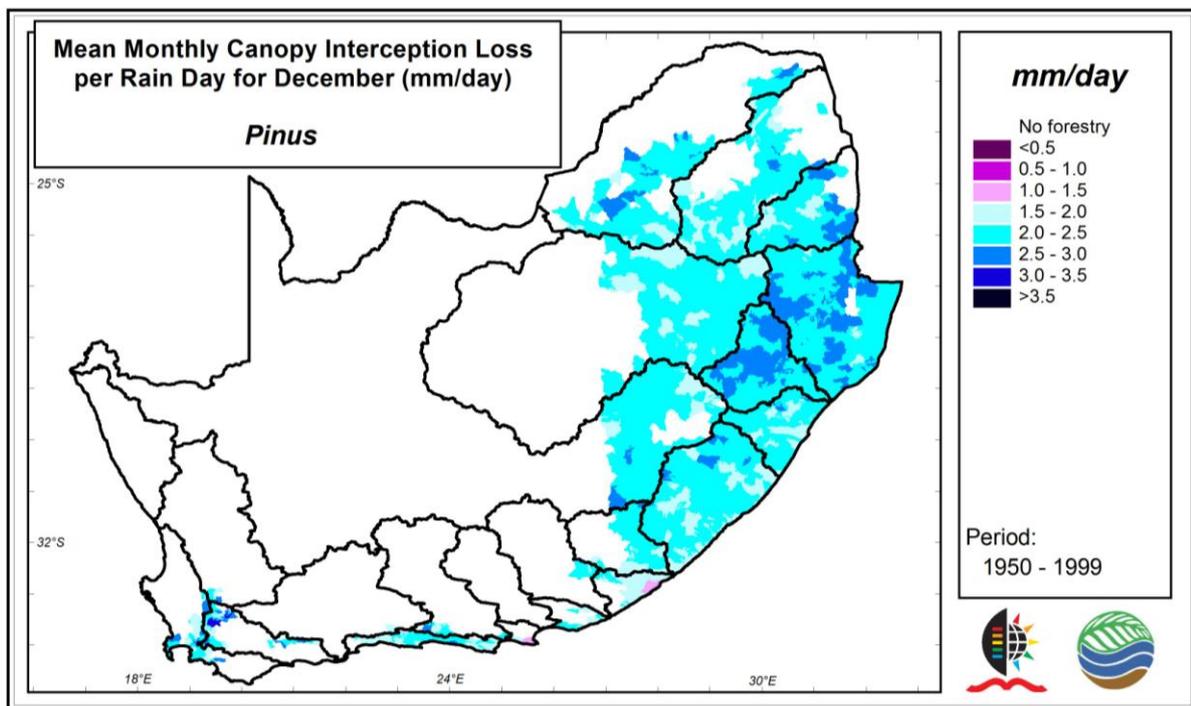
Figure F12　　　Mean canopy interception loss per rainday in December for *Pinus* in South Africa.

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